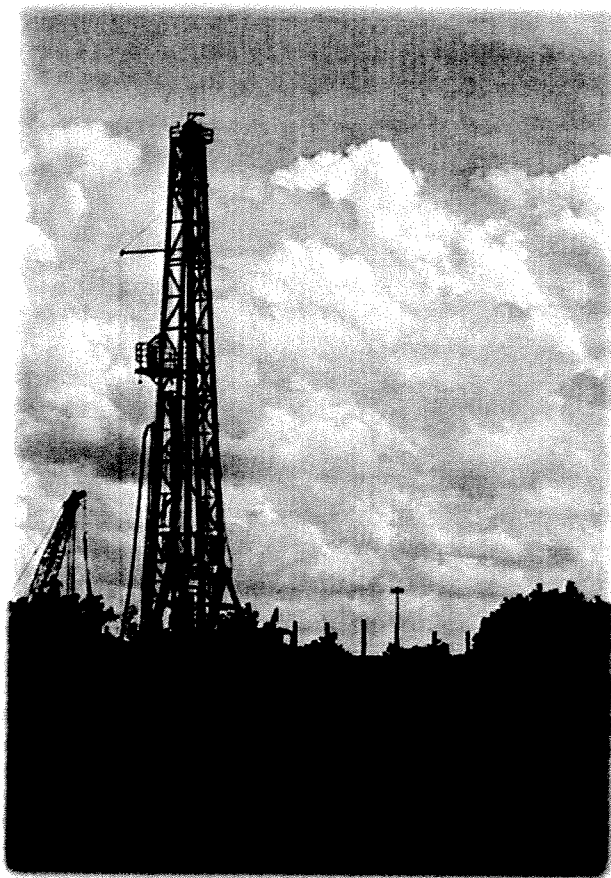


Briefing Paper 1

Addressing the Environmental Risks from Shale Gas Development



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I. Executive Summary

The rapid development of shale gas resources in the past few years has already dramatically affected U.S. energy markets—lowering energy prices and carbon dioxide emissions—and could offer an affordable source of low-carbon energy to reduce dependence on coal and oil.¹ However, the development of shale gas has been linked to a range of local environmental problems, generating a public backlash that threatens to bring production to a halt in some regions. While hydraulic fracturing in particular has been the focus of much controversy, our analysis indicates that the most significant environmental risks associated with the development of shale gas are similar to those associated with conventional onshore gas, including gas migration and groundwater contamination due to faulty well construction, blowouts, and above-ground leaks and spill of waste water and chemicals used during drilling and hydraulic fracturing.

Many technologies and best practices that can minimize the risks associated with shale gas development are already being used by some companies, and more are being developed. The natural gas industry should work with government agencies, environmental organizations, and local communities to develop innovative technologies and practices that can reduce the environmental risks and impacts associated with shale gas development.

Stronger, fully-enforced government regulations are needed in many states to provide sufficient protection to the environment as shale gas development increases. In addition, continued study and improved communication of the environmental risks associated with both individual wells and large scale shale gas development are essential for society to make well-informed decisions about its energy future.

This briefing paper, part of an on-going series on the role of natural gas in the future energy economy, provides an overview of how horizontal drilling and hydraulic fracturing are used to extract shale gas, examines the environmental risks, associated with shale gas development, and

Cover photo: A drilling rig near Shreveport, Louisiana, by danielfoster437.

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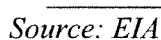
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II. Extracting Natural Gas from Shale

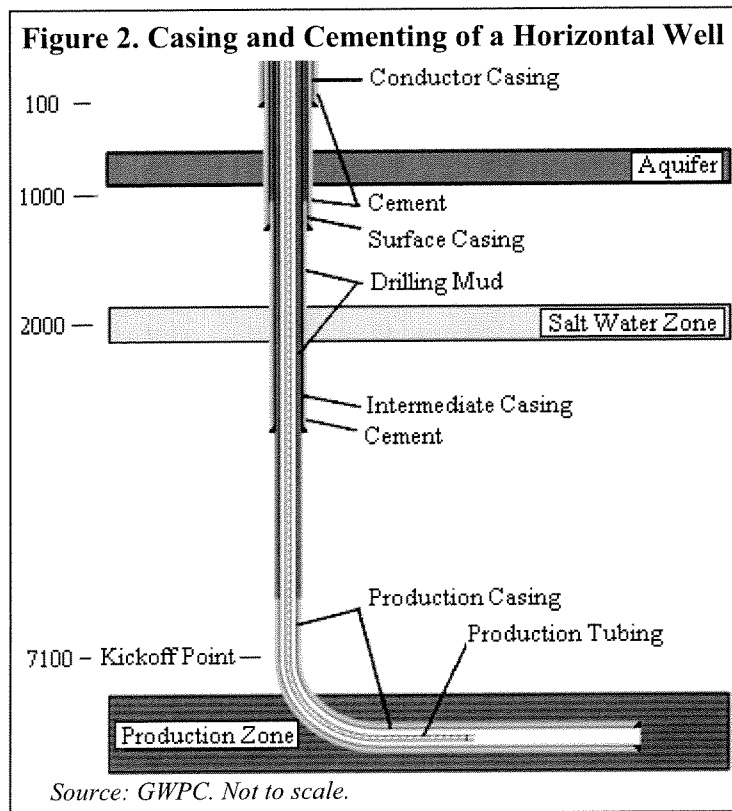
Although the first producing U.S. natural gas well was drilled into a shale formation in New York (in 1821), most commercial drilling during the 19th and 20th centuries targeted gas that has migrated out of its source rock and accumulated in permeable reservoirs such as sandstone formations.² Unlike these “conventional” reservoirs, whose relatively high permeability enables producers to extract gas using vertical wells, shale is a much “tighter,” less permeable rock. As a result, methane molecules cannot flow easily through shale and a vertical well is only able to drain gas only from a very small volume of the rock surrounding it, which generally prevents vertical wells from producing sufficient gas to be economical.

Figure 1. Map of Shale Gas Plays, Lower 48 States



Oil and gas drilling generally begins in the same way in both vertical and horizontal wells. Operators insert an initial length of steel pipe, called “conductor casing,” into a vertical wellbore soon after drilling begins in order to stabilize the well as it passes through the shallow, often unconsolidated sediments and soils near the Earth’s surface.⁵ (See Figure 2.) Then, operators continue drilling vertically and insert surface casing, which most states require to extend from the ground’s surface past the depth of all underground sources of drinking water (USDW’s).⁶

Operators then pump cement into the casing, followed by water, to push the cement out through the bottom of the casing and back up into the space between the surface casing and the wellbore (called the “annulus”) until it is entirely filled. Almost all states require the surface casing to be fully-cemented before drilling is allowed to continue.⁷ After the surface casing has been cemented into place, regulators may require operators to install blowout prevention equipment (BOPE) at the surface to prevent any pressurized fluids encountered during drilling from moving up the well through the space between the drill pipe and the surface casing.⁸



After allowing the cement behind the casing to set, operators continue drilling for a short distance, typically 10 to 20 feet, and test the integrity of the cement by pressurizing the well. They then continue drilling vertically until state regulations may require the insertion of intermediate casing, which can be used to help stabilize deep wells. In addition, between the base of the surface casing and the target gas-bearing shale formations, wellbores pass through thousands of feet of rock formations. These formations may contain hydrocarbons, including natural gas, or briny water containing highly concentrated salts and other contaminants. Intermediate casing is designed to isolate such formations from each other and the wellbore, preventing contamination

of the gas that will be produced and of freshwater aquifers near the Earth’s surface.

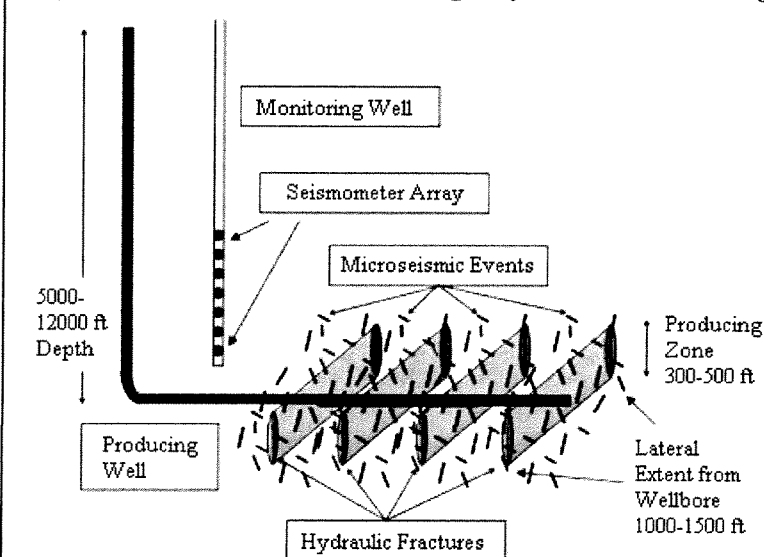
When drilling a horizontal well, operators begin turning or “kicking off” the drill when they near the top of the target formation or “production zone,” until the wellbore runs through the formation horizontally. Horizontal drilling, which can extend up to 10,000 feet, vastly increases the wellbore’s contact with the gas-bearing formation relative to vertical drilling, which would be limited to the thickness of the formation—less than 300 feet in most major U.S. shale plays.⁹

After drilling the horizontal section of the well, operators run a string of “production casing” into the well and cement it in place. They then “perforate” the production casing using small explosive charges at intervals along the horizontal wellbore where they intend to hydraulically fracture the shale.

Hydraulic fracturing was first used in the late 1940s, and has since become a common technique to enhance the production of low permeability formations, especially unconventional reservoirs such as tight sands, coal beds, and deep shales.¹⁰ Hydraulic fracturing is a technically complex process. Because most horizontal wells are quite long, operators conduct fracturing in stages, starting at the tip or “toe” and proceeding toward the end closest to the vertical portion or “heel” of the foot-shaped wellbore. A wellbore that extends 5,000 feet horizontally within a shale layer, for example, might be hydraulically fractured 10 to 15 times at intervals several hundred feet apart. Each perforation interval is isolated in sequence so that only a single section of the well is hydraulically fractured at a given time.

During a hydraulic fracturing operation, operators pump fracturing fluid at high pressure through the perforations in a section of the casing. The chemical composition of the fracturing fluid, as well as the rate and pressure at which it is pumped into the shale, are tailored to the specific properties of each shale formation and, to some extent, each well. When the pressure increases to a sufficient level, it causes a hydraulic fracture or “hydrofracture” to open in the rock, propagating along a plane more or less perpendicular to the path of the wellbore.¹¹ (See Figure

Figure 3. Schematic of Multi-stage Hydraulic Fracturing



When multi-stage hydraulic fracturing is performed, the induced microearthquakes generated during each stage are so small they can be detected only using highly sensitive seismometers placed in nearby monitoring wells. The microseismic events occur in the rock distributed around each of the hydraulic fracture planes. The hydraulic fracturing is done sequentially in 10 to 20 stages. Only four stages are shown here for simplicity. The figure is not to scale.

3.) A typical hydrofracture is designed to propagate horizontally about 500 to 800 feet away from the well in each direction and vertically for the thickness of the shale. Operators monitor and control the fracture pressure to prevent vertical propagation beyond the thickness of the gas-producing shale layer.¹²

One of the most novel discoveries in the Barnett Shale was the possibility of using “slickwater” as a fracturing fluid in deep shale formations. Unlike the highly viscous gels used previously to fracture conventional formations, slickwater is a more dilute, low-viscosity water-based fluid designed to carry a small amount of sand into fractures to

prop them open after the pumping stops, allowing gas to escape. Chemical additives are designed

to inhibit scale and bacterial growth in the wellbore, reduce friction, and generally improve the effectiveness of the fracture job. Slickwater works well in shale gas reservoirs because its low viscosity allows the fracturing fluid to leak out of hydraulic fractures into many small, naturally occurring fractures in the shale.

Slickwater increases water pressure in these microfractures, inducing shear-slip, or micro-seismic events that generally have magnitudes of less than -1.5 on the Richter scale—about as much energy as is released by a gallon of milk dropped from chest height to the floor. Because of the small magnitudes of these events, which represent micro-earthquakes about one-millionth the size of tremors that might be detected by inhabitants of a populated area, operators must deploy ultrasensitive seismometers in nearby monitoring wells in order to detect them.¹³ (See Figure 4.)

Figure 4 shows microseismic data from a well drilled in the Barnett Shale and hydraulically fractured with slickwater in 11 stages. The locations of the microseismic events generated during slickwater hydraulic fracturing provides a picture of where the hydrofractures propagated. This information is important to operators because the microseismic events define the portion of the reservoir stimulated during hydraulic fracturing, increasing the shale's permeability and allowing gas molecules to flow more easily into the production casing.

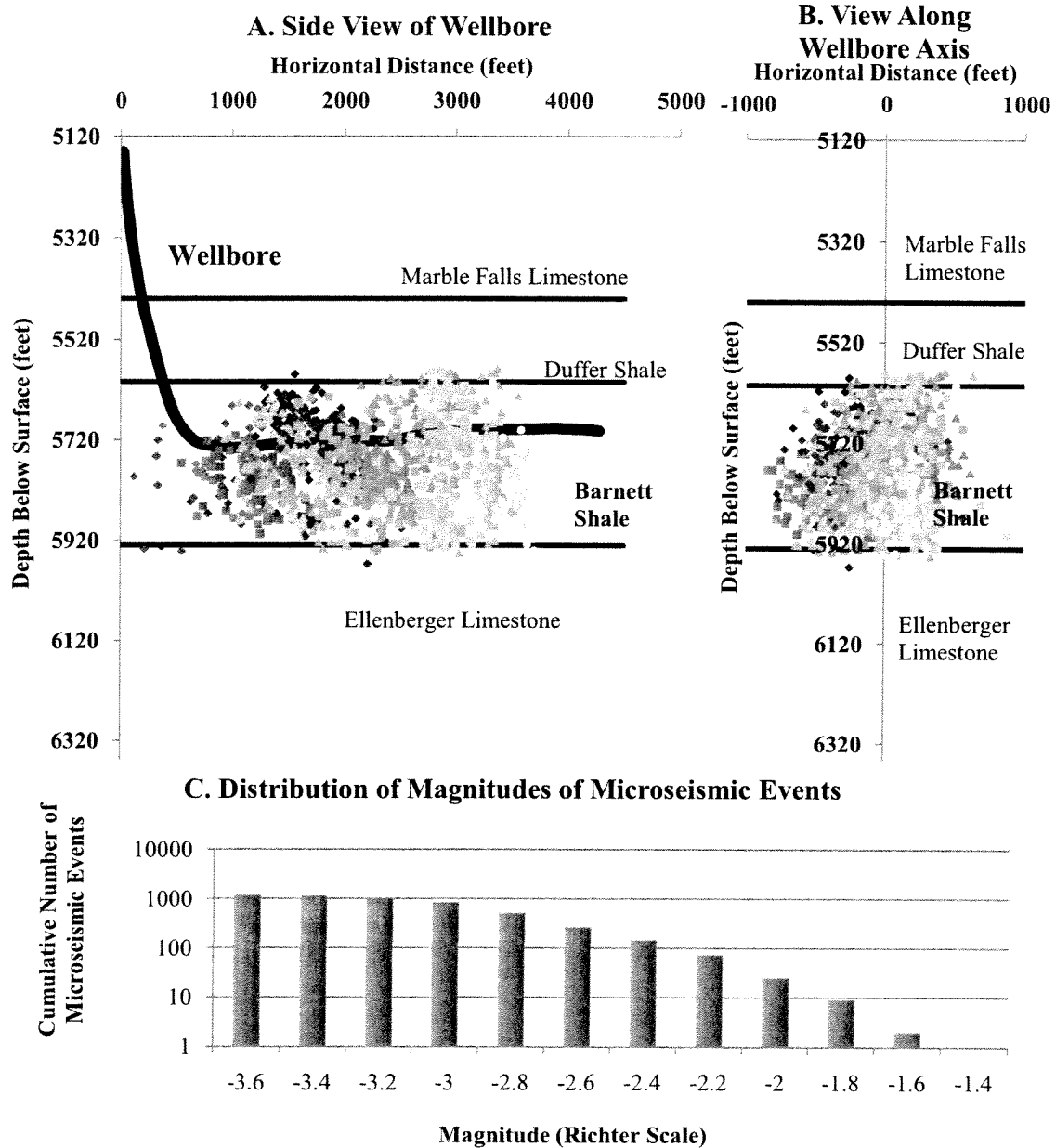
The above-mentioned well targeted a portion of the Barnett Shale about 330 feet thick and at depths between about 5,600 and 5,930 feet below the surface. The horizontal wellbore is roughly 3,800 feet long. Monitoring detected microseismic activity over the entire thickness of the shale, about 150 feet above and 200 feet below the wellbore (Figure 4A), and about 500 to 700 feet to its sides (Figure 4B). Monitoring did not detect microseismic activity any significant distances above or below the shale formation, suggesting that the design of this fracture job successfully confined stimulation to the target formation. In this case, the propagation of fractures into the underlying Ellenberger Limestone, which contains highly saline brine, would have allowed brine to contaminate the gas in the Barnett Shale, decreasing the efficiency and increasing the cost of its extraction. No microseismic events with magnitudes greater than -1.6 were detected.

Drilling and fracturing a typical horizontal well in the Marcellus shale takes about three weeks to complete and costs about \$3.5 to \$4.5 million.¹⁴ After hydraulic fracturing is complete, gas begins to flow out of the well to the surface, where it is processed, compressed, and transported to markets through pipelines. During this period, maintenance may be performed on the well, but much of the equipment used for drilling and fracturing the well is used to drill another horizontal well from the same well pad and wellbore or removed for use at other sites. Each unconventional well's production rate declines rapidly after the first few months of production. While the great majority of gas is produced during the first few years of production, a well could continue to produce for five to ten years before becoming uneconomical.¹⁵ In some cases, a well may be fractured again to restimulate production, but while research is underway to improve the performance of refracturing, it is not currently used in most shale gas wells.¹⁶

When a well becomes uneconomical, state regulations require operators to permanently plug it with cement or another material. The majority of gas-producing states require plugs to be placed through producing zones and from the surface to the base of ground water. Plugs are intended to prevent fluid, which might include hydrocarbons, formation water, and fracturing fluid absorbed

by the target formation, from migrating along the wellbore to other layers of rock and potentially contaminating ground water after the well has been abandoned.¹⁷

Figure 4. Microseismic Diagrams of Typical Hydraulic Fracturing Job in the Barnett Shale



Each dot in Figure 4A and B represents a microseismic event induced during hydraulic fracturing of an actual well in the Barnett Shale, with each color representing a distinct fracturing stage. Figure 4C displays the distribution of these microseismic events by magnitude. Figures are not to scale.

Source: Data courtesy of the Stanford Department of Geophysics

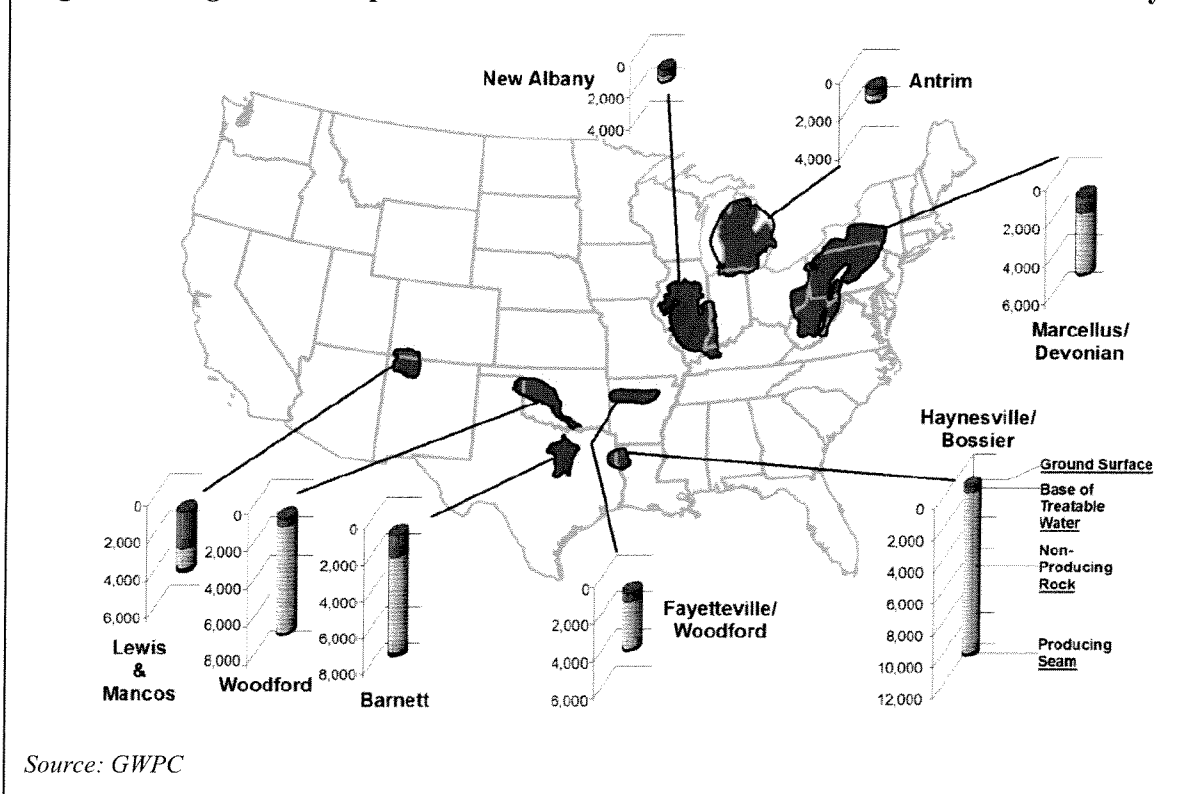
III. Environmental Risks and Best Practices

Shale gas has received a good deal of attention recently for the potential negative impacts that its development may have on the environments and communities in which it occurs. Instances of water contamination, air pollution, and earthquakes have been blamed on gas extraction activities. A thorough understanding of the techniques used to extract gas from shale formations and the safeguards that exist to prevent environmental damage is critical to assessing the sources and magnitudes of risk involved in shale gas development.

Subsurface Contamination of Ground Water

A frequently expressed concern about shale gas development is that subsurface hydraulic fracturing operations in deep shale formations might create fractures that extend well beyond the target formation to water aquifers, allowing methane, contaminants naturally occurring in formation water, and fracturing fluids to migrate from the target formation into drinking water supplies. With the notable exceptions of the shallow Antrim and New Albany Shales, many thousands of feet of rock separate most major gas-bearing shale formations in the United States from the base of aquifers that contain drinkable water.¹⁸ (See Figure 5.)

Figure 5. Target Shale Depth and Base of Treatable Groundwater in Select Shale Plays



Because the direct contamination of underground sources of drinking water from fractures created by hydraulic fracturing would require hydrofractures to propagate several thousand feet

beyond the upward boundary of the target formation through many layers of rock, such contamination is highly unlikely to occur in deep shale formations during well-designed fracture jobs. For example, the top of the Marcellus Shale, which runs from upstate New York through Pennsylvania, West Virginia, and parts of Ohio, lies from 4,000 to 8,500 feet below the surface.¹⁹ The deepest underground sources of drinking water in this region lie about 850 feet below the surface.²⁰ Geologists estimate that there is at least a half mile of rock between the natural gas deposits and the groundwater, including nine layers of impermeable shale, each of which acts as a barrier to vertical propagation of both natural and artificial fractures.²¹

As mentioned earlier, seismic monitoring is an essential tool for assuring that hydraulic fracturing is inducing microseismic activity only within the shale gas reservoir. Yet only about three percent of the ~75,000 hydraulic fracturing stages conducted in the United States in 2009 were seismically monitored.²² Public confidence in the safety of hydraulic fracturing would be greatly improved by more frequent microseismic monitoring and public dissemination of the results.

Failure of the cement or casing surrounding the wellbore poses a far greater risk to water supplies. If the annulus is improperly sealed, natural gas, fracturing fluids, and formation water containing high concentrations of dissolved solids may be communicated directly along the outside of the wellbore among the target formation, drinking water aquifers, and layers of rock in between. For example, in 2007, a well that had been drilled almost 4,000 feet into a tight sand formation in Bainbridge, Ohio was not properly sealed with cement, allowing gas from a shale layer above the target tight sand formation to travel through the annulus into an underground source of drinking water. The methane eventually built up until an explosion in a resident's basement alerted state officials to the problem.²³

A variety of tools exist to help producers and regulators minimize the risk of cement and casing failures. The American Petroleum Institute (API) develops and updates standards and "recommended practices" for oil and gas exploration and production activities.²⁴ Many state regulations require steel casing and cement used in oil and gas well construction to meet standards set by API or other organizations.²⁵ Frequent monitoring and testing also allow producers and regulators to check the integrity of casing and cement jobs. Many states require operators to perform a test such as a cement bond log, which measures the quality of the cement-casing and cement-formation bonds.²⁶ Ensuring that these tests are conducted and heeded in accordance with regulations, and requiring them in states where they are currently voluntary, are essential to preventing accidents such as occurred in Bainbridge.

Blowouts

Recent gas well blowouts in Pennsylvania and West Virginia during drilling operations in the Marcellus Shale, set against the backdrop of the recent offshore blowout and oil spill in the Gulf of Mexico, underscore the environmental and public risks associated with drilling into highly pressurized zones of hydrocarbons and introducing pressurized fluids during hydraulic fracturing.²⁷ At the time of writing this article, the causes of all three blowouts were still under investigation. Operators in Pennsylvania reported that that blowout occurred because the blowout preventer proved inadequate to deal with higher-than-anticipated pressures.²⁸ In West Virginia,

drillers reportedly encountered an unexpected pocket of methane in an abandoned coal mine only about 1,000 feet below the surface, and a blowout preventer had not yet been installed.²⁹

Such disasters stress the need for gathering accurate information about the subsurface and ensuring that personnel on drill sites are trained to deal with unusual and unexpected situations, including blowouts. Even if drilling and well construction are carried out in full compliance with local, state, and federal regulations, and industry best practices are followed, many decisions during drilling and fracturing operations must be made by individuals, and training and experience, together with full enforcement of strong regulations and adoption of industry best practices, are critical to the protection of the public and the environment.

Seismic Risks

Another subsurface risk that has received attention recently is the possibility that drilling and hydraulically fracturing shale gas wells might cause low-magnitude earthquakes. In 2008 and 2009, the town of Cleburne, Texas, experienced several clusters of weak earthquakes all registering 3.3 or less on the Richter scale.³⁰ Since the town had never registered an earthquake in its 142-year history, some residents wondered if the recent increase in local drilling activity associated with the Barnett Shale might be responsible. A study by seismologists with the University of Texas and Southern Methodist University found no conclusive link between hydraulic fracturing and these earthquakes but indicated that the injection of waste water from gas operations into numerous saltwater disposal wells that were being operated in the vicinity could have caused the seismic activity.³¹ Over 200 such wells exist in the Barnett Shale, and are the preferred means of waste water disposal for operators in the area.³²

While the hydraulic fracturing process does create a large number of microseismic events, or micro-earthquakes, the magnitudes of these are generally too small to be detected at the surface. Figure 4C shows the cumulative frequency distribution of microseismic events of different size in a Barnett Shale well. Altogether, a downhole seismometer array deployed in a nearby well detected about 1,000 micro-earthquakes. The biggest micro-earthquakes have a magnitude of about -1.6. An earthquake of this size represents slip of less than a hundredth of an inch, about the thickness of a human hair, on a pre-existing fault only a couple of feet across. The number of extremely small earthquakes (less than a magnitude of about -2.8) tapers off because they are so small that they cannot be detected.

Underground fluid injection is an integral part not only of hydraulic fracturing, but of waste water disposal in injection wells, some geothermal energy projects, and carbon dioxide sequestration. The seismic monitoring of hydraulic fracture jobs discussed earlier is critical to improving understanding of how underground injection might spark unexpectedly high-magnitude seismic activity.

Surface Water and Soil Contamination

Because of the quantities of chemicals that must be stored at drilling sites and the volumes of liquid and solid waste that are produced, significant care must be taken that these materials do not contaminate surface water and soil during their transport, storage, and disposal.

Fluids used for slickwater hydraulic fracturing are typically more than 98 percent fresh water and sand by volume, with the remainder made up of chemicals that improve the treatment's effectiveness, such as thickeners and friction reducers, and protect the production casing, such as corrosion inhibitors and biocides.³³ These fluids are designed by service companies that tailor fracturing treatments to suit the needs of a particular job. In a 2009 survey of six service companies and 12 chemical providers, the New York State Department of Environmental Conservation received a list of some 200 chemical additives that companies might use in fracturing fluids.³⁴

Because the fluids in each fracturing treatment would contain a different subset of these chemicals, and because these chemicals could be hazardous in sufficient concentrations, public disclosure of the chemicals used in hydraulic fracturing on a site-by-site basis is necessary to enable regulatory agencies, health professionals, and citizens to conduct baseline water testing and respond appropriately should contamination or exposure occur. A number of companies are investigating use of more environmentally benign fracturing fluids.³⁵ These would also help limit the environmental and health risks posed by fracturing fluids in the case of contamination.

Chemicals to be used in fracturing fluids are generally stored at drilling sites in tanks before they are mixed with water in preparation for a fracturing job. Under the Emergency Planning and Community Right to Know Act of 1986 (EPCRA), companies must post Material Safety Data Sheets (MSDSs) that list the properties and any health effects of chemicals stored in quantities of more than 10,000 pounds.³⁶ Disclosure of chemicals stored in smaller quantities is not currently required by law, and access to MSDSs can often be limited. Several ongoing efforts would require greater disclosure of fracturing fluids, including a provision in draft climate legislation introduced by Senators John Kerry (D-MA) and Joe Lieberman (I-CT) in May 2010 that would amend EPCRA to mandate the disclosure of all chemicals used on public websites.³⁷

After each fracturing stage, the fracturing fluid, along with any water originally present in the shale formation, is “flowed back” through the wellbore to the surface. Flowback and water produced during a well's lifetime can contain naturally occurring formation water that is millions of years old and therefore can display high concentrations of salts, naturally occurring radioactive material (NORM), and other contaminants including arsenic, benzene, and mercury.³⁸ As a result, the water produced during hydraulic fracturing must be disposed of properly. The “flowback” period typically lasts for periods of hours to weeks, although some injected water can continue to be produced along with gas several months after production has started.³⁹ In the Marcellus Shale, approximately 25 percent of the water injected during hydraulic fracturing operations may be produced during flowback.⁴⁰

Flowback water is dealt with differently in different states. In the Barnett, Fayetteville, Haynesville, Woodford, Antrim, and New Albany Shales, the primary disposal method has been injection into underground saline aquifers, such as the Ellenberger Limestone that underlies the Barnett formation.⁴¹ While injection is regulated at the federal level under the Safe Drinking Water Act (SDWA), the availability of adequate disposal wells is a major issue that needs to be addressed for shale gas development to take place. There are tens of thousands of licensed

injection wells in Texas, but because of political and geological constraints, many fewer exist in the Marcellus Shale. The state of Pennsylvania currently only has about 10 Class II wells.⁴²

As a result, one option for dealing with flowback water from wells in the Marcellus Shale is disposal at municipal waste water treatment facilities, which generally discharge treated water into surface water bodies such as rivers and streams.⁴³ Current waste water treatment facilities in the Marcellus are insufficient to handle the volumes of fluids that would be produced were shale gas development to increase significantly. In addition, they may not be designed to handle the highly saline water produced by gas drilling.

In late 2008 and 2009, there were significant spikes in the level of total dissolved solids (TDS) in Pennsylvania's Monongahela River, which supplies drinking water to approximately 350,000 people. Since flowback contains large amounts of total dissolved solids (TDS), and drilling fluids constituted up to 20 percent of the waste water being treated by some facilities, the Pennsylvania Department of Environmental Protection (PADEP) ordered these facilities to restrict their intake of drilling waste water.⁴⁴ PADEP reported that TDS levels, which also can be influenced by abandoned mine drainage, stormwater runoff, and discharges from industrial or sewage treatment plants, exceeded standards at least twice more in 2009.⁴⁵

Given the constraints on both underground injection and treatment and discharge in the Marcellus Shale, serious investment will be needed in advancing treatment technologies that enable companies to reuse fluids for subsequent fracturing jobs. As flowback comprises only 25 percent of the water injected into a given well in the Marcellus, treated flowback water could be diluted with fresh water and re-injected. Recycling water minimizes both the overall amount of water used for fracturing and the amount that must be disposed of. Many water treatment processes are currently being investigated that could be potentially be used at large scale and have a significant impact on this problem.⁴⁶

Finally, one of the problematic aspects of handling flowback water is the temporary storage and transport of such fluids prior to treatment or disposal. In many cases, fluids may be stored in lined or even unlined open evaporation pits.⁴⁷ Even if the produced water does not seep directly into the soil, a heavy rain can cause a pit to overflow and create contaminated runoff.⁴⁸ Storing produced water in enclosed steel tanks, a practice already used in some wells, would reduce the risk of contamination while improving water retention for subsequent reuse.⁴⁹

In addition, equipment used to move fluids between storage tanks or pits and the wellhead must be monitored and tested regularly to prevent spills, and precautions must be taken while transporting produced water to injection or treatment sites, whether via pipeline or truck. In May 2009, PADEP discovered that two leaky joints in a pipeline carrying waste water from gas wells to a disposal site had resulted in the release of about 4,200 gallons of waste water into Cross Creek, causing the deaths of some fish and invertebrates.⁵⁰ Range Resources, the owner of the wells, was fined for this violation of Pennsylvania's environmental statutes, as well as for another spill that occurred in October 2009.⁵¹

Other Surface Impacts

Drilling operations require significant above-ground development. In addition to the well pad itself, roads may need to be built and gathering infrastructure installed to bring the natural gas from the wellhead to a pipeline that, for a typical well in the Marcellus Shale, may require the development of several acres of land. Total land use can be reduced by drilling multiple wells from a single well pad, as is done in areas of steep topography or environmental sensitivity. Nonetheless, because so many wells have to be drilled and appreciable infrastructure developed, it is important to do as much as possible to minimize the overall impact on local communities. Land use decisions affect a wide range of stakeholders including the landowners, neighbors and surrounding communities. Permitting procedures will need to evaluate the needs of each of the stakeholders and include clear and enforceable remediation strategies to ensure minimal impact and maximum restoration of the land associated with natural gas production.

The trucks used to transport equipment, fracturing fluid ingredients, and water to the wellpad, drilling rigs, compressors, and pumps all emit air pollutants, including carbon dioxide, nitrogen and sulfur oxides (NO_x and SO_x), and particulate matter. Volatile organic compounds (VOCs) and other pollutants associated with natural gas and fracturing fluids can enter the air from wells and evaporation pits. In addition, natural gas, whose main component is methane, is itself a greenhouse gas more potent than carbon dioxide and could represent a significant source of emissions during the gas production process.⁵²

Many technologies and practices to reduce venting and leakage during gas production and transport have been compiled by the U.S. EPA's Natural Gas STAR program.⁵³ Emissions of gases that contribute to local air pollution, public health risks and climate change can be reduced by available control technologies, improved monitoring, and more efficient production operations. (The impacts of natural gas development with air quality will be the focus of a future briefing paper by the Natural Gas and Sustainable Energy Initiative.)

Even compared with drilling, which might use up to a million gallons of water per well, hydraulic fracturing is a water-intensive procedure, requiring between 2 and 8 million gallons per well fractured.⁵⁴ In the Barnett Shale, for example, an average of almost 3 million gallons of water is used per well, the great majority of which is used for hydraulic fracturing.⁵⁵ Since development of this resource will require tens of thousands of shale gas wells to be drilled, the required volumes of water are dramatic.

Any set of water use regulations must take into account local hydrology and competing uses for the water in a given area. Operators and regulators must work together to explore opportunities to reduce water use and increase recycling of produced water. Greater reuse of fracturing fluids would reduce demands on community water supplies. Steps can also be taken to utilize excess water during peak seasonal run-off and to try to use less water during slickwater fracturing operations. (The water requirements for natural gas development will be the focus of a future briefing paper by the Natural Gas and Sustainable Energy Initiative.)

While a well is being drilled and completed, operators are generally working around the clock for several weeks. Drilling sites generate significant amounts of noise pollution, although noise

can be reduced through the construction of sound barriers.⁵⁶ Gas development can also affect communities in less tangible ways. While it may stimulate the local economy and provide jobs, gas development may also lead to increased traffic and greater strains on public resources. Operators must work with local stakeholders to minimize the impact of gas development activities on a community's resources and quality of life.

BOX: Current Regulatory Framework Governing Shale Gas Development

Most regulation of oil and gas development is currently left to the states, where regulatory bodies are in charge of enforcing state environmental laws as well as rules and regulations specific to oil and gas production. Rules and regulations developed by state agencies such as the Colorado Oil and Gas Conservation Commission, the Texas Railroad Commission, or the Pennsylvania Department of Environmental Protection govern the specifics of gas production, requiring producers to obtain permits before drilling, and requiring certain standards and practices to be used during well construction, hydraulic fracturing, waste handling, and well plugging. State regulations also deal with tanks and pits as well as any chemical or waste water spills.

Currently, there is significant variation in the particulars of these rules and regulations from state to state. For example, in a 2009 survey of the 27 largest gas-producing states, the Ground Water Protection Council (GWPC) found that 25 states required surface casing to be set below the deepest groundwater, 21 require a cement set-up period or test such as a cement bond log, 10 require companies to list chemicals or pressures used during hydraulic fracturing, and none requires companies to list an estimate of how much of this fracturing fluid flows back to the surface after a well has been fractured. The non-profit STRONGER (State Review of Oil and Natural Gas Environmental Regulations) has been updating guidelines for reviews of state programs since 1999. A list of states that have completed initial and follow-up reviews is available on STRONGER's website (www.strongerinc.org).

In addition to these state rules and regulations, some federal environmental regulations also apply to shale gas development. For example, the Clean Water Act regulates contaminated storm water runoff and surface discharges of water from drilling sites, and the 1986 Emergency Planning and Community Right-to-Know Act (EPCRA) requires companies to post material safety data sheets describing the properties and health effects of any chemicals stored in quantities that exceed 10,000 pounds. In some cases, states may obtain authority to enforce a federal law. The Safe Drinking Water Act (SDWA), which regulates the underground injection of waste water from gas wells, though not hydraulic fracturing, is one example of a federal law which allows state regulatory agencies to obtain primacy over enforcement if they demonstrate that they can do so to the minimum standards laid forth by the Environmental Protection Agency.

Source: See Endnotes 2 and 5 for this section.

IV. Conclusion

New supplies of gas from shale could provide many U.S. states with an attractive, lower-carbon transition fuel on the path to a fully renewable energy supply, while providing jobs and generating appreciable revenue. However, these opportunities cannot be realized unless the environmental risks posed by shale gas development are managed effectively. Our analysis suggests that while shale gas development poses significant risks to the environment, including faulty well construction, blowouts, and above-ground contamination due to leaks and spills of fracturing fluids and waste water, technologies and best practices exist that can help manage these risks.

Best practices are currently being applied by some producers in some locations, but not by all producers in all locations. Enforcing strong regulations is necessary to ensure broader adoption of these practices and to minimize risk to the environment. In addition, if increased shale gas development is to be undertaken responsibly, the cumulative risks of developing thousands of wells must be considered. Ongoing studies by the Environmental Protection Agency and others examining the environmental impacts of hydraulic fracturing will arm state and federal decision makers with critical information upon which to base future regulations.

By developing and adopting innovative best practices, industry can take a proactive role in addressing the environmental risks associated with shale gas development. The Houston Advanced Research Center and Texas A&M University are working with companies, environmental organizations, universities, government laboratories, state and federal agencies, and others to reduce the environmental impact of drilling and production. The Environmentally Friendly Exploration and Production program focuses on solutions to reduce the footprint of drilling activities, ensure the safe transport and disposal of drilling fluids and cuttings, lower air and noise pollution, and minimize other risks to the environment.⁵⁷

Robust regulatory oversight is an important ingredient to assure environmental and public protection. Under current U.S. laws, some aspects of shale gas development are regulated by the Clean Water Act, the Clean Air Act, and the Safe Drinking Water Act, but regulation of drilling and hydraulic fracturing is left largely to the state level where regulatory capacity and enforcement, as well as the regulations themselves, vary widely.

The state of Colorado recently revised its oil and gas rules to strengthen protections for the local environment.⁵⁸ The new rules, which went into effect on April 1, 2009, were devised after a boom in gas production from coal bed methane and tight sands was linked to both environmental and public health problems as well as permitting bottlenecks. Colorado Governor Bill Ritter has argued that the public assurance that these rules created was as an important prerequisite for adoption of Colorado's 2010 Clean Air-Clean Jobs Act. That Act requires Colorado's rate regulated utilities to retire or re-power some 900 megawatts of coal-fired power plants, displacing them primarily with natural gas.⁵⁹ However, many independent producers feel that they were excluded from what was touted as a multi-stakeholder process and argue that the Colorado Oil and Gas Conservation Commission did not fully account for the increased costs the new rules would impose, while some environmentalists feel that the revisions did not go far enough.⁶⁰

Colorado's example provides valuable lessons to other states pursuing their own reform of oil and gas regulations. The Wyoming Oil and Gas Conservation Commission passed a package of new oil and gas drilling rules on June 8, 2010. These rules make Wyoming the first state to require operators to disclose the composition and concentration of chemicals used in hydraulic fracturing.⁶¹ Other shale-producing states may soon follow suit.⁶²

New York, a relative newcomer to the modern oil and gas industry, has been the site of a contentious debate over future development of the state's gas resources in the Marcellus Shale. The New York Department of Environmental Conservation (NYSDEC) has been charged with updating rules regulating horizontal drilling and high-volume hydraulic fracturing and is currently evaluating public comments on a draft Supplemental Generic Environmental Impact Statement that it released in September 2009.⁶³ In the meantime, 10 bills relating to shale gas development, including one that would place a moratorium on drilling until 120 days after the EPA's study of hydraulic fracturing is completed, are making their way through the state legislature.⁶⁴ In neighboring Pennsylvania, where over 564 wells were drilled in the Marcellus Shale during the first half of 2010, Governor Ed Rendell has said that he would sign a bill calling for a three-year moratorium on new leasing of state forest land for gas exploration while potential environmental impacts are studied.⁶⁵

The experiences of Colorado, Wyoming, Pennsylvania, and New York have demonstrated that strong public pressure exists for stricter oversight of the oil and gas industry and that state regulators can and will move forward in strengthening their own regulations. If they are produced responsibly, shale gas resources in the United States could play a central role in building a low-carbon energy economy. Greater outreach and public education about shale gas development are clearly necessary to enable the many stakeholders engaged in shale gas development to work together to find the most effective technological and regulatory solutions for developing shale gas resources while protecting the environment and public interest.

Endnotes

- ¹ Worldwatch Institute, *The Role of Natural Gas in a Low-Carbon Energy Economy* (Washington, DC: April 2010).
- ² Groundwater Protection Council (GWPC), *Modern Shale Gas Development in the United States: A Primer*, prepared for the U.S. Department of Energy, National Energy Technology Laboratory (NETL) with ALL Consulting (Oklahoma City, OK: April 2009), p. 13.
- ³ Figure 1 from U.S. Department of Energy, Energy Information Administration (EIA), "Shale Gas Plays, Lower 48 States," available at www.eia.doe.gov/oil_gas/rpd/shale_gas.pdf, viewed 7 July 2010.
- ⁴ Calculated based on 2009 U.S. crude oil production of 5.31 million barrels per day, and conversion factor of 1 billion cubic feet NG = 0.19 million barrels of oil equivalent. Shale gas production rates for 2009 from Vello Kuuskraa, Advanced Resources International, "The 'Paradigm Shift' in U.S. and Worldwide Natural Gas Supplies," presentation at Global Unconventional Gas Conference 2010, Amsterdam, 17 June 2010. U.S. crude oil production from EIA, "Crude Oil Production," Petroleum Navigator, available at www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbldpd_a.htm, viewed 7 July 2010. Conversion factor from BP, *Statistical Review of World Energy June 2010* (London: 2010).
- ⁵ Figure 2 from GWPC, *State Oil and Natural Gas Regulations Designed to Protect Water Resources*, prepared for NETL (Oklahoma City, OK: May 2009), p. 20.
- ⁶ State regulations requiring surface casing to be set below the deepest ground water exist in 25 of the 27 oil and gas-producing states surveyed by the GWPC in 2008. Twenty-four states required surface casing to be cemented along its entire length. GWPC and NETL, *State Oil and Gas Regulations Designed to Protect Water Resources* (Oklahoma City: May 2009), p. 19.
- ⁷ Twenty-four of 25 states surveyed required surface casing to be cemented along its entire length, per *Ibid.*
- ⁸ Not all states require blowout preventers for all wells. Colorado's new rules regulating oil and gas drilling, which may be considered a best management practice, requires operators to: install blowout preventer equipment (BOPE) on any well expected to flow, inspect it daily, ensure that it has a sufficient rating to accommodate the maximum anticipated surface pressure, and ensure that rig employees understand and can operate it. Operators must also pressure test the casing and BOPE after each new string is added, and proceed with drilling only when this equipment has been tested and found to be functional. Colorado Oil and Gas Conservation Commission (COGCC), "Rules and Regulations, 603 (i) (as of 1 April 2009)," available at <http://cogcc.state.co.us/>.
- ⁹ The Barnett Shale is a notable exception, with a thickness of 100 to 600 feet. GWPC, *op. cit.* note 2, p. 17.
- ¹⁰ GWPC, *op. cit.* note 5, p. 21.
- ¹¹ Figure 3 created by Mark Zoback, Stanford University.
- ¹² M.J. Economides and K.G. Nolte, eds., *Reservoir Simulation* (West Sussex, U.K.: John Wiley & Sons, Ltd., 2000).
- ¹³ Figure 4 was created by Bradford Copithorne and Mark Zoback and is based on proprietary data made available by a gas company currently operating in the Barnett Shale.
- ¹⁴ Thomas R. Driscoll, "Marcellus Could Become Largest Gas Play," *Barclays Capital*, 15 March 2010.
- ¹⁵ S.M. Currie, D. Ilk, and T.A. Blasingame, "Continuous Estimation of Ultimate Recovery, SPE 132352," paper presented at 2010 SPE Unconventional Gas Conference, Pittsburgh, PA, 23–25 February 2010.
- ¹⁶ E. Siebrits et al., "Refracture Reorientation Enhances Gas Production in Barnett Shale Tight Gas Wells," presented at the 2000 Society of Petroleum Engineers Annual Technical Conference and Exhibition, Dallas, TX 1–4 October 2000; Mukul Sharma, "Improved Reservoir Access through Refracture Treatments in Tight Gas Sands and Shales," presentation (Golden, CO: 15 April 2009).
- ¹⁷ GWPC, *op. cit.*, note 5, p. 27.
- ¹⁸ Figure 5 from GWPC, *op. cit.*, note 2, p. 54.

-
- ¹⁹ Daniel Arthur, *Hydraulic Fracturing Considerations for Natural Gas Wells of the Marcellus Shale*, presented at the GWPC 2008 Annual Forum. (Cincinnati, OH: 21-24 September 2008),
- ²⁰ GWPC, op. cit., note 2, p. 17.
- ²¹ Arthur, op. cit. note 19
- ²² Kent Perry, Gas Technology Institute (GTI), personal communication with Mark Zoback, 9 June, 2010.
- ²³ Ohio Department of Natural Resources, Division of Mineral Resources Management, “*Report on the Investigation of the Natural Gas Invasion of Aquifers in Bainbridge Township of Geauga County, Ohio*,” (Columbus, OH: 1 September 2008
- ²⁴ American Petroleum Institute, “E & P Safety Standards,” www.api.org/standards/epstandards/index.cfm, viewed 12 July 2010.
- ²⁵ “Addendum: State Oil and Gas Regulations Reference Document,” in GWPC op. cit. notes 5. pp. 66-264.
- ²⁶ GWPC, op. cit., note 5, pp. 19-21.
- ²⁷ Katie Howell, “Marcellus Well in Pa. Blows Out,” *E&E News PM*, 4 June 2010; Vicki Smith, “Burned in W. Va. Gas Well bBlast Likely to Survive,” *Charleston Gazette*, 7 June 2010
- ²⁸ Howell, op. cit., note 27
- ²⁹ Smith, op. cit., note 37.
- ³⁰ Ben Casselman, “Temblors Rattle Texas Town,” *Wall Street Journal*, 12 June 2009
- ³¹ Cliff Frohlich et al., “Dallas-Fort Worth Earthquakes Coincident with Activity Associated with Natural Gas Production,” *The Leading Edge* (Society of Exploration Geophysicists), March 2010, pp. 270-75.
- ³² Disposal well count from Ibid.
- ³³ GWPC, op. cit., note 2, p. 63.
- ³⁴ New York State Department of Environmental Conservation (NYSDEC), *Draft Supplemental General Environmental Impact Statement* (Albany: 30 September 2009), pp. 5-35 to 5-40.
- ³⁵ Energy companies such as Halliburton and BJ Services are developing “environmentally focused” fracturing fluids that do not contain BETX (benzene, ethyl benzene, toluene and xylene) components and that meet the requirements of the Energy Act of 2005 and the Clean Water Act. Halliburton, “Ultra Clean Fracturing Fluid Technology” (December 2007), available at www.halliburton.com/ps/default.aspx?pageid=1844&navid=105&prodid=PRN::JSHSB7C4S ; BJ Services, “Environmentally Friendly Fracturing Fluids” (2008) available at www.bjservices.com/website/index.nsf/WebPages/Shale-Papers-Expandable-Section/
- ³⁶ GWPC, op. cit., note 2, p. 41.
- ³⁷ American Power Act, Sec. 4131.
- ³⁸ Amy Mall, et al., *Drilling Down: Protecting Western Communities from the Health and Environmental Effects of Oil and Gas Production* (New York: Natural Resources Defense Council: September 2007), p. vi.
- ³⁹ GWPC, op. cit., note 2, p. 66.
- ⁴⁰ Thomas Hayes, GTI, personal communication with Mark Zoback, June 1, 2010.
- ⁴¹ GWPC, op. cit., note 2, p. 69.
- ⁴² Jeff Jollie, U.S. Environmental Protection Agency (EPA), Office of Ground Water and Drinking Water, personal communication with Saya Kitasei. 21 April 2010.
- ⁴³ GWPC, op. cit., note 2, p. 69.
- ⁴⁴ Pennsylvania Department of Environmental Protection (PADEP), “DEP Investigates Source of Elevated Total Dissolved Solids in Monongahela River,” press release (Harrisburg, PA: 22 October 2008).
- ⁴⁵ Ibid.; Riverkeeper, “Impacts and Incidents Involving High-Volume Hydraulic Fracturing From Across the Country,” Appendix 1 to comments on NYSDEC Draft Supplemental General Environmental

Impact Statement, available at www.riverkeeper.org/wp-content/uploads/2010/01/Riverkeeper-DSGEIS-Comments-Appendix-1-Case-Studies.pdf

- ⁴⁶ A.W. Gaudlip, L.O. Paugh and T.D. Hayes, “Marcellus Shale Water Management Challenges in Pennsylvania, SPE -119898-PP,” paper presented at the 2008 Shale Gas Production Conference, Ft. Worth, TX, 16-18 November, 2008; M.E. Blauch, “Developing Effective and Environmentally Suitable Fracturing Fluids using Hydraulic Fracturing Flowback Waters, SPE 131784,” paper presented at 2010 SPE Unconventional Gas Conference, Pittsburgh, PA, 23-25 February 2010.
- ⁴⁷ GWPC, op. cit., note 5, p. 29.
- ⁴⁸ Delaware River Keeper, “Natural Gas Well Drilling and Production: In the Upper Delaware River Watershed,” www.delawareriverkeeper.org/resources/Factsheets/Drilling_and_Production.pdf
- ⁴⁹ GWPC, op. cit., note 5, p. 28-9.
- ⁵⁰ PADEP, Oil and Gas Management Program, Inspection Record #1802228 (Harrisburg, PA: 27 May 2009)
- ⁵¹ PADEP, “DEP Penalizes Range Resources \$141,175 for Spill in High Quality Waterway,” press release (Harrisburg, PA: 14 May 2010)
- ⁵² Methane leakage could be responsible for 71 percent of total greenhouse gas emissions from the U.S. natural gas industry if the IPCC’s recent 20-year global warming potential is used. Jerome Blackman, U.S. EPA, “Methane Emissions Reductions: Barriers, Opportunities and Possibilities for Oil and Natural Gas,” presentation at Natural Gas STAR Program 2009 Annual Implementation Workshop, 20 October 2009
- ⁵³ EPA, Natural Gas STAR Program, “Recommended Technologies and Practices,” viewed 26 May 2010.
- ⁵⁴ This range is given for a 4,000-foot lateral wellbore in the Marcellus, but concurs with estimates in other plays. The amount of water required depends on both the length of the well and the properties of the target formation. NYSDEC, op. cit., note 30, p. 5-72.
- ⁵⁵ GWPC, op. cit., note 2, p. 64.
- ⁵⁶ Ibid., p. 49.
- ⁵⁷ Environmentally Friendly Exploration and Production program Web Site, www.efdsystems.org/Home/tabid/1253/Default.aspx, viewed 12 July 2010.
- ⁵⁸ Colorado Oil and Gas Conservation Commission, “COGCC Amended Rules,” available at <http://cogcc.state.co.us/>, viewed 7 June 2010.
- ⁵⁹ Office of Governor Bill Ritter, Jr., “Gov. Ritter Signs Historic Clean Air-Clean Jobs Act,” press release (Denver: 19 April 2010)
- ⁶⁰ David Williams, “Ritter’s oil and gas rules one year later,” *Colorado Independent* (25 May 2010), available at <http://coloradoindependent.com/54104/ritters-oil-and-gas-rules-one-year-later>, viewed 8 June 2010.
- ⁶¹ Phil Taylor, “Wyoming set to Approve Fracking Disclosure Rules,” *Land Letter*, 3 June 2010
- ⁶² David Williams, “Major Gas-producing States Debating Colorado-style Drilling Regulations,” *Colorado Independent*, 21 May 2010
- ⁶³ NYSDEC, *Draft Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program* (updated 26 October 2009), www.dec.ny.gov/energy/58440.html, updated 26 October 2009 .
- ⁶⁴ Jon Campbell, “Bill to Halt Hydro-fracking Close to Assembly Vote,” *PressConnects.com* (4 June 2010)
- ⁶⁵ PADEP, “2010 Wells Drilled by Operator as of 06/03/2010,” www.dep.state.pa.us/dep/deputate/minres/oilgas/2010%20Wells%20Drilled%20by%20Operator.htm, viewed 7 June 2010; Marc Levy and Joe Mandak, “Rendell Backs Moratorium on Leasing Public Land for Gas Drilling,” *Ithaca Journal*, 11 May 2010.



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Lester R. Brown

Lester Russell Brown (né en 1934) est un agroéconomiste et analyste environnemental américain. Pionnier des recherches sur le développement durable, il a été l'un des premiers, et des plus prolifiques, à écrire sur les problèmes liés à l'écologie.

Il est le fondateur de l'institut Worldwatch ainsi que du Earth Policy Institute, organisation non gouvernementale basée à Washington D.C., dont il est actuellement le président.

Bien qu'il ait écrit plus de vingt ouvrages, Lester Brown est connu principalement pour ses livres « *Plan B 2.0 : Rescuing a Planet Under Stress and a Civilization in Trouble.*, ("sauvetage d'une planète sous pression et d'une Civilisation en crise") » et « *Eco-économie : Une autre croissance est possible, écologique et durable* ».

Avec des publications traduites dans plus de quarante langues, il est l'un des auteurs-essayistes les plus largement diffusés dans le monde. Lester R. Brown a d'ailleurs été décrit par le *Washington Post* comme étant "l'un des penseurs les plus influents de notre époque".

Jean-Louis Borloo, ministre français de l'Écologie, du Développement et de l'Aménagement Durables, reconnaît explicitement que Lester R. Brown est l'une des principales sources d'inspiration des travaux du "Grenelle de l'Environnement".^[1]



Lester Brown

Biographie

Lester R. Brown fut d'abord agriculteur, cultivateur de tomates avec ses frères plus jeunes, et alors qu'il était encore écolier puis étudiant à l'université. Il obtient un diplôme en agronomie à l'université de Rutgers en 1955, puis il passe six mois en Inde où il se familiarise avec les problèmes d'alimentation. En 1959 il est analyste en agriculture internationale au ministère américain de l'agriculture. Il obtient ensuite des diplômes en économie agricole à l'université du Maryland, et en administration publique à Harvard.

En 1966, le gouvernement américain le nomme administrateur du Service du développement agricole à l'étranger. En 1969, il quitte le gouvernement pour fonder le *Overseas Development Council*. En 1974 avec le soutien de la fondation Rockefeller, Lester Brown fonde l'institut Worldwatch, le premier institut voué à l'analyse des questions d'environnement mondial.

Bibliographie

- *Man, Land and Food* (1963)
- *Increasing World Food Output* (1965)
- *Seeds of Change* (1970)
- *Man and His Environment: Food* (with Gail Finsterbusch) (1972)
- *World Without Borders* (1972)
- *In the Human Interest* (1974)
- *By Bread Alone* (with Erik Eckholm) (1974)
- *The Twenty-Ninth Day* (1978)
- *Running on Empty* (with Colin Norman & Christopher Flavin) (1979)
- *Building a Sustainable Society* (1981)
- *State of the World* (with others) (1984-2001)
- *Vital Signs* (with others) (1992-2001)
- *Eko Keizai Kakumei: Environmental Trends Reshaping The Global Economy* (1998) (in Japanese)
- *Saving the Planet: How to Shape an Environmentally Sustainable Global Economy* (1992)
- *Full House: Reassessing the Earth's Population Carrying Capacity* (1995)
- *Who Will Feed China?: Wake-Up Call for a Small Planet* (1995)
- *Tough Choices: Facing the Challenge of Food Scarcity* (1996)
- *Beyond Malthus: Nineteen Dimensions of the Population Challenge* (with Gary Gardner and Brian Halweil) (1999)
- *Eco-Economy: Building an Economy for the Earth* (2001)
- *Plan B: Rescuing a Planet Under Stress and a Civilization in Trouble* (2003)
- *Outgrowing the Earth: The Food Security Challenge in an Age of Falling Water Tables and Rising Temperatures* (2004)
- **(en)** *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble* (2006). **(en)** Lecture en ligne ou à télécharger ^[2]
- **(fr)** *Le Plan B Pour un pacte écologique mondial - Traduction française de Plan B 2.0 préface de Nicolas Hulot* (2007)
- **(en)** *Plan B 3.0: Mobilizing to Save Civilization* (2008) Lecture possible en ligne ^[3]

Liens

- **(fr)** Articles de Lester R. Brown ^[4], traduits en français par l'organisme de formation Ecologik Business, partenaire du Earth Policy Institute.
- **(fr)** Émission de radio *Terre à Terre* sur France-Culture (2008) 54 mn ^[5] Long entretien avec Lester R. Brown à propos de son livre *Plan B 2.0*, à l'occasion de la parution de la traduction française. Écoute en ligne possible pendant plusieurs semaines après la diffusion initiale du 5 janvier 2008 (format Real Audio).
- **(fr)** Interview vidéo par le magazine *Télérama* en trois questions clés ^[6] le 7 novembre 2007.
- **(fr)** *Plan B 2.0 Pour un pacte écologique mondial* ^[7] Revue de presse autour de la traduction française de *Plan B 2.0* et de la conférence à l'UNESCO le 7 novembre 2007
- **(fr)** Article du magazine *Capital* (2005) ^[8] où sont expliquées, en français, son analyse et ses préconisations.
- **(en)** Earth Policy Institute ^[9] - Biographie de Lester R. Brown.
- **(en)** Entretien avec Lester R. Brown sur *PLAN B: Rescuing a Planet Under Stress and a Civilization in Trouble*, ^[10] au Carnegie Council.
- **(en)** Une interview de Lester R. Brown sur la crise de l'eau ^[11] (format MP3)

Références

- [1] Entretien du 10 Octobre 2007 (<http://www.radiofrance.fr/franceinter/em/septdix/index.php?id=60365>) dans l'émission "le 7/10" sur *France Inter*
 - [2] <http://www.earth-policy.org/Books/PB2/Contents.htm>
 - [3] <http://www.earth-policy.org/Books/PB3/Contents.htm>
 - [4] <http://www.ecologik-business.com/newsletters/index.html>
 - [5] http://www.radiofrance.fr/chaines/france-culture2/emissions/terre_a_terre/fiche.php?diffusion_id=57477
 - [6] http://www.telarama.fr/monde/21722-trois_questions_1_ecologiste_americain_lester_brown_le_penseur_qui_monte.php
 - [7] <http://www.soufflecourt.com/revuepresse.html>
 - [8] <http://docsmartinez.free.fr/dotclear/index.php?2006/04/26/31-lester-brown-une-grave-crise-alimentaire-menace-le-monde>
 - [9] http://www.earth-policy.org/About/Lester_bio.htm
 - [10] <http://www.cceia.org/resources/transcripts/1037.html>
 - [11] <http://www.altruists.org/f254>
-

Sources et contributeurs de l'article

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PROFESSIONAL EXPERIENCE:

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1981-1984	Chief, Branch of Tectonophysics, U.S. Geological Survey
1976-1984	Geophysicist, U.S. Geological Survey
1980-1981	Deputy Chief, Office of Earthquake Studies, U.S. Geological Survey
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1975-1976	Research Associate, National Research Council Postdoctoral Fellowship
1975	Visiting Scientist, Ruhr University, Bochum, Germany
1973-1975	Geophysicist, U.S. Geological Survey
1971-1973	Research Assistant, Stanford University
1969-1971	Geophysicist, Amoco Production Company

HONORS AND AWARDS:

2010-Present	Visiting Professor, Lawrence Berkeley National Laboratory
2008	Walter H. Bucher Medal, American Geophysical Union
2006	New Zealand Geophysics Prize for 2006 (with John Townend)
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2005	Named Benjamin M. Page Professor of Earth Sciences, Stanford University
2004	Best of What's New 2004, Popular Science (EarthScope's San Andreas Fault Observatory at Depth)
2004	School of Earth Sciences Excellence in Teaching Award
1999	Outstanding Alumni Award, University of Arizona Department of Geosciences
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1998	University Fellow, Stanford University
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1998	Elected Fellow, American Geophysical Union
1989	Senior Research Scientist Award, Alexander Von Humboldt Stiftung
1985	Elected Fellow, American Association for the Advancement of Science
1984	Elected Fellow, Geological Society of America
1975	National Research Council Post-Doctoral Fellowship

UNIVERSITY SERVICE

2010-Present	Faculty Senate Steering Committee
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2009-2010	University Fact Finder, Reappointment Appeal
2004-2008	University Capital Planning Group
1995-2008	Member, Earth Systems Steering Committee
2003-2004	Member University Advisory Board
2002-2004	Chair, Planning and Policy Board
2001-2004	Provost's Committee on Recreational use of the Dish
2002-2003	Chair, Subcommittee on University Awards
2001-2002	Earth Systems Review Committee
2001	Provost's Task Force on College Rankings
2000	Provost Search Committee
2000	General Counsel Evaluation Panel
1999-2000	Member, Stanford Communications Council
1999-2000	Chair, Faculty Senate
1996-2000	Coordinator, SME, Earth Sciences Track
1997-1998	Committee on Committees

1996-1998	Chair, Committee of 15
1991-1997	Chair, Geophysics Department

PROFESSIONAL ACTIVITIES

2010-Present	Member, NAE Committee on Deepwater Horizon Accident
2010-Present	Earth Science Chair, Program Advisory Committee, DUSEL Program
2009-Present	Board of Directors, Research Partnership for Secure Energy for America
2009-Present	Board of Directors and Vice President, American Rock Mechanics Association
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2007-Present	Chair, Science of Earthquake Studies Advisory Committee (USGS)
1998-Present	Member, American Association of Petroleum Geologists
1998-Present	Member, Society of Petroleum Engineers
1984-Present	Member, American Association for the Advancement of Science
1983-Present	Member, Geological Society of America
1982-Present	Member, Seismological Society of America
1973-Present	Member, American Geophysical Union
2010	Invited Speaker, University of Munich
2010	Holmes Lecture, Syracuse University
2010	EUG, Invited Speaker
2010	Invited Speaker, USGS/GCEP Conference on CO2 Seals
2010	Distinguished Scientist Lecture, Lawrence Berkeley National Lab
2010	Invited Speaker, Unconventional Gas Conference
2010	Invited Speaker, American Geophysical Union
2010	Invited Lecture, Univ. S. Carolina
2010	Cuyler Memorial Lecture, University of Texas
2010	Netherlands Earth Science Review Committee
2010	Invited Speaker, University of Wisconsin
2009	Invited Speaker, Sed. Basin Workshop, Abu Dhabi
2009	Invited Speaker, ConocoPhillips Workshop on Geomechanics
2009	Invited Speaker, ILP Symposium, Clarmont-Ferrand, France
2009	Invited Speaker, COGA Meeting
2009	Invited Speaker, GCEP Annual Meeting
2009	Invited Speaker, SPE Shale Forum
2008	Invited Speaker, GeoForschung Potsdam, Germany
2008	Invited Speaker, MIT
2008	Invited Speaker, World Stress Map Conference
2008	Keynote Speaker, ARMA Symposium
2008	Invited Speaker, Hedberg Conference
2008	Invited Speaker, GEO2008, Bahrain
2002-2008	EarthScope Facilities Executive Committee/EarthScope Management Team
2007	Invited Speaker, New Zealand Geological Survey
2007	Invited Speaker, Geological Society of America Pardee Symposium
2007	Invited Speaker, SPE Forum, Kananaskis, Canada
2007	Invited Speaker, Geological Society of London Bicentennial
2007	Invited Speaker, University of Toronto
2007	Invited Speaker, Geological Survey of Canada
2007	Invited Speaker, University of Oregon
2006-2007	IODP Review Committee
2000-2007	Member, Begleitende Kommission, Heidelberg Academy of Science, World Stress Map Project
2006	Invited Speaker, GeoForschungZentrum, Potsdam, Germany
2006	Invited Speaker, National Institute for Geophysical Volcanology, Rome
2006	Invited Speaker, Seismological Society of America
2006	Invited Speaker, American Association for the Advancement of Science
2006	Invited Speaker, German Geophysical Society
2006	Invited Speaker, Annual Milton Dobrin Memorial Lecture, Houston Geophysical Society
2000-2006	Member, DOSECC Board of Directors
1999-2006	Chair, Science Advisory Group, International Continental Drilling Program
2005	Invited Speaker, Sandia National Laboratory, Distinguished Speaker
2005	Invited Speaker, Scripps Institute of Oceanography
2005	invited Speaker, University of Kansas
2005	Invited Speaker, University of Southern California

2005 Invited Speaker, American Geophysical Union
 2005 Invited Speaker, Society of Exploration Geophysicists
 2001-2005 Science Director, Western Resources Project

COURSES TAUGHT:

<i>Year</i>	<i>Quarter</i>	<i>Course Number</i>	<i>Course Title</i>	<i>Total Enrollment</i>
2009	Fall	385K	Crustal Mechanics	3
2009	Fall	385L	Quake Seismology & Stress	7
2009	Fall	400	Geophysics Research	7
2009	Spring	385K	Crustal Mechanics	3
2009	Spring	802	TGR Dissertation	1
2009	Spring	400	Geophysics Research	5
2009	Spring	385L	Quake Seismology & Stress	4
2009	Winter	385K	Crustal Mechanics	5
2009	Winter	202	Reservoir Geomechanics	30
2009	Winter	185K	Crustal Mechanics	1
2009	Winter	385L	Quake Seismology & Stress	8
2009	Winter	400	Geophysics Research	6
2009	Winter	802	TGR Dissertation	1
2008	Fall	802	TGR Dissertation Mark Zoback on sabbatical	1
2008	Fall	400	Geophysics Research Mark Zoback on sabbatical	6
2008	Fall	385K	Crustal Mechanics Mark Zoback on sabbatical	2
2008	Fall	385L	Earthquake Seismology, Deformation & Stress Mark Zoback on sabbatical	9
2008	Spring	400	Geophysics Research Mark Zoback on sabbatical	5
2008	Spring	385L	Quake Seismology & Stress Mark Zoback on sabbatical	6
2008	Spring	385K	Crustal Mechanics Mark Zoback on sabbatical	2
2008	Winter	290	Tectonophysics Mark Zoback on sabbatical taught by Paul Hagin	10
2008	Winter	385K	Crustal Mechanics Mark Zoback on sabbatical	1
2008	Winter	400	Geophysics Research	4
2008	Winter	185K	Geophysics Research Mark Zoback on sabbatical	1
2008	Winter	385L	Quake Seismology & Stress Mark Zoback on sabbatical	9
2008	Winter	399	Teaching Experience in Geophysics	1
2007	Fall	400	Geophysics Research	3
2007	Fall	801	TGR Project	1
2007	Fall	802	TGR Dissertation	2
2007	Fall	385K	Crustal Mechanics	2
2007	Fall	385L	Quake, Seismology & Stress	5
2007	Spring	385L	Quake Seismology & Stress	4
2007	Spring	185L	Quake Seismology & Stress	1
2007	Spring	255	Report on Energy Industry Training	3
2007	Spring	802	TGR Dissertation	1
2007	Spring	400	Geophysics Research	4
2007	Summer	400	Geophysics Research	1
2007	Summer	802	TGR Dissertation	1
2007	Winter	385K	Crustal Mechanics	1
2007	Winter	385L	Quake Seismology & Stress	5
2007	Winter	399	Teaching Experience in Geophysics	1
2007	Winter	400	Geophysics Research	4
2007	Winter	802	TGR Dissertation	1
2007	Winter	202	Reservoir Geomechanics	16
2006	Fall	385K	Crustal Mechanics	2
2006	Fall	385L	Quake Seismology & Stress	4
2006	Fall	110	Geosphere	35
2006	Fall	400	Geophysics Research	2
2006	Fall	802	TGR Dissertation	4
2006	Winter	GP 202	Reservoir Geomechanics	9
2005		GP202	Reservoir Geomechanics	16

2005	Fall	GP102	Geosphere	1
2004		GP185L	Quake Seismology & Stress (with Beroza, Segall)	1
2004		GP 400	Geophysics Research	5
2004		GP 802	TGR Dissertation	2
2004		GP202	Reservoir Geomechanics	23
2004		GP385K	Crustal Mechanics	4
2004		GP802	TGR Dissertation	1
2004		GP399	Teaching Experience	1
2004		GP400	Geophysics	7
2004		GP 385K	Crustal Mechanics	4
2004	Fall	GP385L	Quake Seismology & Stress (with Beroza, Segall)	5
2003		GP110/ESP110	Geosphere (with Arrigo)	66
2003		GP385K	Crustal Mechanics (with Arrigo)	9
2003		GP385L	Quake Seismology & Stress (with Beroza, Segall)	6
2003		GP399	Teaching Experience	3
2003		GP400	Geophysics Research	26
2003		GP202	Reservoir Geomechanics	13
2003		GP290	Tectonophysics	13
2003		GP802	TGR Dissertation	3
2003		GP385K	Crustal Mechanics	4
2003		GP802	TGR Dissertation	1
2003		GP400	Geophysics Research	7
2002		GP102	Earth, Oceans and Atmospheres (with Arrigo)	9
2002		GP202	Reservoir Geomechanics	11
2002		GP385L	Earthquake Seismology (with Beroza, Segall)	16
2002		GP185L	Quake Seismology and Stress (with Beroza, Segall)	3
2002		GP385K	Crustal Mechanics	6
2002		GP399	Teaching Experience	2
2002		GP400	Geophysics Research	24
2001		GP385	Earthquake Seismology, Deformation and Stress (with Beroza, Segall)	2
2001		GP/PE202	Reservoir Geomechanics	14
2001		GP185	Earthquake Seismology, Deformation and Stress (with Beroza, Segall)	1
2001		GP400	Research	5
2001		GP385	Earthquake Seismology (w/Beroza and Segall)	5
2001		SME4	Earth, Oceans, and Atmospheres (with Arrigo)	22
2001		GP399	Teaching Experience	1
2001		GP385	Crustal Mechanics	1
2001		GP399	Teaching Experience	1
2001		GP400	Research	5
2001		GP185	Earthquake Seismology, Deformation and Stress (Beroza, Segall)	1
2001		GP385	Earthquake Seismology, Deformation and Stress (with Beroza, Segall)	4
2001		GP290	Tectonophysics	21
2001		GP385	Crustal Mechanics	1
2001		GP400	Research	6
2001		GP400	Research	6
2000		GP400	Research	22
2000		GP202	Reservoir Geomechanics	8
2000		GP385	Borehole Geophysics	3
2000		GP385	Earthquake Seismology (w/Beroza and Segall)	8
1999		GP385	Borehole Geophysics	2
1999		SME101	Earth Resources and Sustainability of life (with three others)	122
1999		GP385	Earthquake Seismology (w/Beroza and Segall)	17
1999		GP400	Research	16
1998		SME001	Earth Resources and Sustainability of life (McWilliams and others)	149
1998		GP385	Earthquake Seismology	5
1998		GP385	Borehole Geophysics	3
1998		GP202	Reservoir Geomechanics	10

1998	GP400	Research	18
			1,021

ADVISEES RECEIVING DEGREES:

<i>Year</i>	<i>Name and Dissertation or Research Title</i>	<i>Degree</i>	<i>Place of Employment</i>
2008	Laura Chiaramonte: "Geomechanical Characterization and Reservoir Simulation of a CO2 Sequestration Project in a Mature Oil Field, Teapot Dome, WY"	Ph.D.	Lawrence Berkeley National Laboratory
2007	Pijush Paul: "A methodology for incorporating geomechanically-based fault damage zone models into reservoir simulation "	Ph.D.	ConocoPhillips
2007	Hannah Ross: "Carbon Dioxide Sequestration and Enhanced Coalbed Methane Recovery in unmineable coalbeds of the powder river basin, Wyoming"	Ph.D.	BP
2007	Amy Day-Lewis: "Characterization and modeling of in situ stress heterogeneity"	Ph.D.	GMI
2007	Ellen Mallman: "Stress triggering of earthquakes and subsidence in the Louisiana coastal zone due to hydrocarbon production"	Ph.D.	BP
2007	Amie Lucier: "Geomechanical Analysis applied to geological carbon dioxide sequestration, induced seismicity in deep mines, and detection of stress-induced seismicity in deep mines, and detection of stress-induced velocity anisotropy in sub-salt environments"	Ph.D.	Shell
2007	John Vermilyen	M.S.	PhD student Stanford
2005	Naomi Boness: "Physical properties and multi-scale seismic anisotropy in the crust surrounding the San Andreas fault near Parkfield, CA."	Ph.D.	ChevronTexaco
2004	Alvin Wing-Ka Chan: "Louisiana Coastal Wetland Loss: The role of Hydrocarbon Production"	Ph.D.	Shell Oil Co., Houston, TX
2004	Sang-Min Kim	M.S.	PhD Student, Univ. of California, Berkeley
2004	Lourdes Colmenares: "Geomechanics and the Effectiveness of Wellbore Completion Methods of Coalbed Methane Wells in the Powder River Basin"	Ph.D.	Language School, Switzerland
2003	Paul Hagin: "Application of viscoelastic models and rate-and-state friction laws to the mechanics of unconsolidated sands"	Ph.D.	Stanford University Crustal Mechanics Laboratory
2003	John Townend: "Mechanical constraints on the strength of the lithosphere and plate-bounding faults"	Ph.D.	Victoria University of Wellington, Wellington, New Zealand
2002	Stephanie Prejean: "The interaction between tectonic and magmatic processes in Long Valley Caldera, California"	Ph.D.	U.S. Geological Survey, Menlo Park, CA 94025
2001	David Wiprut: "Stress, Borehole Stability, and Hydrocarbon Leakage in the Northern North Sea"	Ph.D.	GeoMechanics International, Houston, TX
2000	Balz Grollmund: "Impact of deglaciation on stress and implications for seismicity and hydrocarbon exploration"	Ph.D.	Swiss Reinsurance, Zurich, Switzerland
1999	Thomas Finkbeiner: "In-situ stress, pore pressure, and hydrocarbon migration and accumulation in sedimentary basins"	Ph.D.	Geomechanics Int., Abu Dhabi
1998	Carl Chang: "Time-dependent deformation of unconsolidated reservoir rocks"	Ph.D.	Agilent Technology Palo Alto, CA
1998	Stacy Kerkela	M.S.	Vestek Systems, San Francisco, CA
1998	Sneha Dholakia (with Pollard) (GES)	M.S.	BP, Houston, TX

PUBLICATIONS:

- 2010* Bohnhoff, M., M.D. Zoback, L. Chiaramonte, J.L Gerst and N. Gupta, Seismic Detection of CO2 Leakage along Monitoring Wellbores, International Journal of Greenhouse Gas Controls, v.4, pp.687-697.
- (In Press)* Bohnhoff, M., M.D. Zoback, Oscillation of fluid-filled cracks triggered by degassing of CO2 due to leakage along wellbores, submitted to Journal of Geophysical Research
- 2010 Hagin, P.N. and M.D. Zoback, Inverting for creep strain parameters of uncemented reservoir sands using arbitrary stress-strain data, paper presented at 44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium, Salt Lake City, Utah, June 27-30, 2010, paper ARMA 10-171.
- 2010 Hagin, P.N. and M.D. Zoback, Laboratory studies of the compressibility and permeability of low-rank coal samples from the Powder River Basin, Wyoming, USA, paper presented at 44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium, Salt Lake City, Utah, June 27-30, 2010, paper ARMA 10-170.
- 2010 Natural gas can lead the way, Earth, February issue, p. 86-87.
<http://www.earthmagazine.com/earth/article/2fb-7da-2-1>
- 2010 Sone, H. and M.D. Zoback, Strength, creep and frictional properties of gas shale reservoir rocks, paper presented at 44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium, Salt Lake City, Utah, June 27-30, 2010, paper ARMA 10-463.

- 2010 Zoback, M.D., Climate and intraplate shocks, *Nature*, v. 466, 568-569.
- 2010 Zoback, M.D., S. Hickman and W. Ellsworth, Scientific Drilling into the San Andreas Fault, *EOS*, v. 91, no. 22, June 1, 2010, 197-198.
- 2010 Zoback, M.D., S. Kitasei and B. Copithorne, Addressing the environmental risks from shale gas development, Worldwatch Institute, 19 pp, <http://www.worldwatch.org/files/pdf/Hydraulic%20Fracturing%20Paper.pdf>.
- 2009* Chang, C. and M.D. Zoback, Viscous creep in room-dried unconsolidated Gulf of Mexico shale (I): Experimental results, *Journal of Petroleum Science and Engineering*, v. 69, 239-246.
- 2009* Chang, C. and M.D. Zoback, Viscous creep in room-dried unconsolidated Gulf of Mexico shale (II): Development of a viscoplasticity model, *Journal of Petroleum Science and Engineering*, v.72, 50-55.
- 2009* Lucier, A., M.D. Zoback, V. Heesackers, Z. Reches and S. Murphy, Constraining the far-field stress state near a deep South African Gold Mine, *International Journal of Rock Mechanics and Mining Sciences*, 46 (2009), pp. 555-567.
- 2009* Paul, P., M.D. Zoback and P. Hennings, Fluid Flow in a Fractured Reservoir Using Geomechanically Constrained Fracture Model for Reservoir Simulation - SPE Reservoir Evaluation & Engineering - Formation Evaluation, Aug. 2009, page 562-575.
- 2009* Ross, H.E., P. Hagin, and M.D. Zoback, CO₂ storage and enhanced coalbed methane recovery in unmineable coalbeds of the Powder River Basin, Wyoming: Reservoir characterization and fluid flow simulations, *International Journal of Greenhouse Gas Controls*, v.3, p. 773-786, doi:10.1016/j.ijggc.2009.06.002
- 2008* Lucier, A. and M.D. Zoback, Assessing economic feasibility of regional deep saline aquifer CO₂ injection and sequestration: A geomechanics-based workflow applied to the Rose Run Sandstone in Eastern Ohio, USA, *International Journal of Greenhouse Gas Controls*, DOI:10.1016/j.ijggc.2007.12.002.
- 2008 Lucier, A., M.D. Zoback, V. Heesackers and Z. Reches, Constraining the far-field stress state near a deep South African Gold Mine, ARMA 08-141, in 42nd US Rock Mechanics Symposium, San Francisco, CA.
- 2008* Paul, P. and M.D. Zoback, Wellbore stability study for the SAFOD borehole through the San Andreas Fault, SPE 102781, SPE Drilling and Completion, Dec., 2008, p. 394-408.
- 2008* Ross, H. E. and M.D. Zoback, Sub-hydrostatic pore pressure in coalbed and sand aquifers of the Powder River Basin, WY and MT, and implications for disposal of coalbed-methane -produced water through injection, *Rocky Mountain Geology*, v.43, p. 155-169.
- 2007* Chan, A.W. and M.D. Zoback, The Role of Hydrocarbon Production on Land Subsidence and Fault Reactivation in the Louisiana Coastal Zone, *Journal of Coastal Research*, DOI: 10.2112/05-0553,771-786.
- 2007* Chiamonte, L., M.D. Zoback, J. Friedmann and V. Stamp, Seal integrity and feasibility of CO₂ sequestration in the Teapot Dome EOR pilot: geomechanical site characterization, *Environmental Geology*, DOI 10.1007/s00254-007-0948-7.
- 2007* Colmenares, Lourdes B. and M.D. Zoback, Hydraulic fracturing and wellbore completion of coalbed methane (CBM) wells in the Powder River Basin, Wyoming: Implications for water and gas production, *American Association of Petroleum Geologists Bulletin*, 91,51-67.
- 2007* Fernandez-Ibanez, F., J.I. Soto, M.D. Zoback and J. Morales, Present-day stress field in the Gibraltar Arc (Western Mediterranean), *Jour. Geophys. Res.*, 112, B08404 DOI 10.1029/2006JB004683.
- 2007* Hagin, P. and M.D. Zoback, A dual power law model for prediction and monitoring of long-term compaction in unconsolidated reservoir sands, *Geophysics*, 72(5), E165-E173.
- 2007* Hagin, P., Sleep, N.H. and M.D. Zoback, Application of rate-and-state friction laws to creep compaction of unconsolidated sand under hydrostatic loading conditions, *Jour. Geophys. Res.*, 112, DOI:10.1029/2006JB004286.
- 2007 Harms, U., C. Koeberl and M.D. Zoback (eds), *Continental Scientific Drilling*, Springer-Verlag, Heidelberg, 366 pp.
- 2007* Mallman, E.P. and M.D. Zoback, Assessing elastic Coulomb stress transfer models using seismicity rates in southern California and southwestern Japan, *Jour. Geophys. Res.*, 112, B03304, DOI: 10.1029/2005JB004076.
- 2007* Mallman, E.P. and M.D. Zoback, Subsidence in the Louisiana coastal zone due to hydrocarbon production, *Journal of Coastal Research*, Special Issue 50.
- 2007 Sleep, N.H. and M.D. Zoback, Did Earthquakes Keep the Early Crust Habitable?, *Astrobiology*, 7 (6), DOI:10.1089/ast.2006.0091.
- 2007* Wu, H-Y, K-F Ma, M.D. Zoback, N. Boness, H. Ito, J-H Hung and S. Hickman, Stress orientations of Taiwan Chelungpu-Fault Drilling Project (TCDP) hole-A as observed from geophysical logs, *Geophys. Res. Lett.*, 34 (L01303).
- 2007 Zoback, M.D., *Reservoir Geomechanics: Earth Stress and Rock Mechanics Applied to Exploration, Production and Wellbore Stability*, Cambridge Press, Cambridge Press, 449 pp.
- 2007 Zoback, M.D., S. Hickman and W. Ellsworth, The role of fault zone drilling, in *Earthquake Seismology - Treatise on Geophysics Vol. 4*, ed. H. Kanamori and G. Schubert, Elsevier Ltd., Amsterdam, 649-674.
- 2007 Zoback, M.L. and Zoback, M.D., Lithosphere Stress and Deformation, in *Earthquake Seismology - Treatise on Geophysics Vol. 6*, ed. A. Watts and G. Schubert, Elsevier Ltd., Amsterdam, 253-274.
- 2006* Boness, Naomi L. and M.D. Zoback, A multi-scale study of the mechanisms controlling shear velocity anisotropy in the San Andreas Fault Observatory at Depth, *Geophysics*, 71 (5), F131-F136.
- 2006* Boness, Naomi L. and M.D. Zoback, Mapping Stress and Structurally-Controlled Crustal Shear Velocity Anisotropy in California, *Geology*, 34, 825-828.

- 2006* Chang, Chandong, M.D. Zoback and A. Khaksar, Rock strength and physical property measurements in sedimentary rocks, *Journal of Petroleum Sci. and Engineering*, 51, 223-237.
- 2006* Lucier, A., M.D. Zoback, N. Gupta and T.S. Ramakrishnan, Geomechanical aspects of CO₂ sequestration in a deep saline reservoir in the Ohio River Valley region, *Environmental Geology*, 13 (2), 85-103.
- 2006 Paul, P. and M.D. Zoback, Wellbore Stability Study for the SAFOD Borehole through the San Andreas Fault: SPE 102781, 2006 SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, U.S.A., 24-27 September 2006. [PDF](#)
- 2006* Ross, H., R., Blakely and M.D. Zoback, Testing the utilization of aeromagnetic data for the determination of Curie depth, *Geophysics*, 71 (5), L51-L59.
- 2006* Townend, J. and M.D. Zoback, Stress, strain and mountain-building in central Japan, v.111, B03411, *Jour. Geophys. Res.*
- 2005 Colmenares, L. and M.D. Zoback, Geomechanics and the Effectiveness of Wellbore Completion Methods of Coalbed Methane (CBM) Wells in the Powder River Basin: Implications for Water and Gas Production, in *Special Publication of Wyoming Geological Survey, Report of Investigations 55*, ed. M.D. Zoback, Chapter 6, pp. 127-157.
- 2005* Grollimund, B. and M.D. Zoback, Impact of glacially-induced stress changes on fault seal integrity: Offshore Norway: Reply, *AAPG Bull.*, 89, 275-279.
- 2005 Zoback, M. D., Editor, Wyoming State Geological Survey Report of Investigations #55, Western Resources Project Final Report-Produced Groundwater Associated with Coalbed Natural Gas Production in the Powder River Basin, 157 pages.
- 2004 Boness, N. and M.D. Zoback, Stress-induced seismic velocity anisotropy and physical properties in the SAFOD Pilot hole in Parkfield, CA, SPE/ARMS 04-540, June 5-9, 2004, Houston, Texas.
- 2004* Boness, N. and M.D. Zoback, Stress-induced seismic velocity anisotropy and physical properties in the SAFOD pilot hole in Parkfield, CA., *Geophysical Research Letters*, 31, no. 15, L15S17.
- 2004 Chan, A.W., Hagin, P.N. and Zoback, M.D., Viscoplastic Deformation, Stress and Strain Paths in Unconsolidated Reservoir Sands (Part 2): Field Applications Using Dynamic DARS Analysis, ARMA/NARMS 04-568, Presented at Gulf Rocks 2004, 6th North America Rock Mechanics Symposium (NARMS), Houston, TX June 5-9, 2004
- 2004* Chan, A.W., P.N. Hagin and M.D. Zoback, Viscoplastic Deformation, Stress and Strain Paths in Unconsolidated Reservoir Sands (Part 2): Field Applications Using Dynamic DARS Analysis, SPE/ARMS 04-568,
- 2004* Chery, J., M.D. Zoback and S. Hickman, A mechanical model of the San Andreas fault and SAFOD pilot hole stress measurements, *Geophysical Research Letters*, 31, no. 15, L15S13.
- 2004* Hagin, P.N. and M.D. Zoback, Viscoplastic deformation in unconsolidated reservoir sands (Part I): Laboratory observations and time-dependent end cap models, SPE/ARMS 04-567,
- 2004* Hagin, P.N. and M.D. Zoback, Viscous deformation of unconsolidated reservoir sands (Part I): Time-dependent deformation, frequency dispersion and attenuation, *Geophysics*, Vol. 69, No. 3(May-June 2004); P. 731-741.
- 2004* Hagin, P.N. and M.D. Zoback, Viscous deformation of unconsolidated reservoir sands (Part II): Linear viscoelastic models, *Geophysics*, Vol. 69, No. 3 (May-June 2004); P. 742-751.
- 2004* Hickman, S. and M.D. Zoback, Stress orientations and magnitudes in the SAFOD pilot hole, *Geophysical Research Letters*, Vol. 31, no. 12 and 15, L15S12.
- 2004* Hickman, S., M.D. Zoback and W. Ellsworth, Introduction to special section: Preparing for the San Andreas Fault Observatory at Depth, *Geophysical Research Letters*, 31, no. 15, L12S01.
- 2004 Hippler, S., T. Finkbeiner, A. Lucier and M.D. Zoback, Controls on oil and gas distribution in over-pressured reservoirs, SPE/ARMS 04-568, June 5-9, 2004, Houston, TX.
- 2004* Townend, J. and M.D. Zoback, Regional tectonic stress near the San Andreas fault in central and southern California, *Geophysical Research Letters*, 31, L15S11.
- 2004 Zoback, M.D., Why must earthquakes be this devastating?, in *Outlook*, The Washington Post, Jan. 4, 2004, p. B5.
- 2003 Barton, C.A. and M.D. Zoback, Wellbore Imaging Technologies Applied to Reservoir Geomechanics and Environmental Engineering"" in ""Geological Applications of Well Logs"", M. Lovell and N. Parkinson eds., AAPG Methods in Exploration, No. 13, 229-239.
- 2003* Chanchani, S.K., M.D. Zoback and C. Barton, A case study of hydrocarbon transport along active faults and production-related stress changes in the Monterey formation, California, in *Fracture and In-situ stress characterization of hydrocarbon reservoirs*, Spec. Pub. Geol. Soc. London, ed. M. Ameen, 209, 17-26.
- 2003* Colmenares, L. and M.D. Zoback, Stress field and seismotectonics of northern South America, *Geology*, 31, 721-724.
- 2003* Grollimund, B., and M.D. Zoback, Impact of glacially-induced stress changes on fault seal integrity offshore Norway, in: Davies, R., Handschy, J. eds., AAPG Bull. 87 (3), 493-506.
- 2003* Moos, D., P. Peska, T. Finkbeiner and M.D. Zoback, Comprehensive wellbore stability analysis using quantitative risk assessment, *Jour. Petrol. Sci. and Eng.*, Spec. Issue on Wellbore Stability, eds. Bernt S. Aadnoy, and Seehong Ong, 38, 97-109.
- 2003* Prejean, S., W. Ellsworth, M.D. Zoback and F. Waldhauser, Fault structure and kinematics of the Long Valley caldera region, CA, revealed by high-accuracy earthquake hypocenters and focal mechanism inversions, *Jour. Geophys. Res.*, 107, no. B. 12, ESE 9-1 to 9-19.
- 2003* Zoback, M.D., C.A. Barton, M. Brudy, D.A. Castillo, T. Finkbeiner, B.R. Grollimund, D. B. Moos, P.

- Peska, C.D. Ward, D.J. Wiprut, Determination of stress orientation and magnitude in deep wells, *Int'l Jour. Rock Mech. and Mining Sciences*, 40, 1049-1076.
- 2002 Wiprut, D. and M.D. Zoback, Fault reactivation, leakage potential, and hydrocarbon column heights in the northern North Sea, in *Hydrocarbon Seal Quantification*, A.G. Koestler, R. Hunsdale, eds., Norwegian Petroleum Society (NPF), Special Publication No. 11, Elsevier, Amsterdam, 263 pp.
- 2002 Barton, C.A. and M.D. Zoback, Discrimination of Natural Fractures From Drilling-Induced Wellbore Failures in Wellbore Image Data--Implications for Reservoir Permeability, SPE 78599, in "SPE Reservoir Evaluation and Engineering", June 2002, 249-254.
- 2002 Chan, A.W. and Zoback, Deformation analysis in reservoir space (DARS): A simple formalism for prediction of reservoir deformation with depletion, SPE/ISRM 78174, SPE/ISRM Rock Mechanics Conference, Irving, TX, 20-23 Oct. 2002.
- 2002* Colmenares, L.B. and M.D. Zoback, A statistical evaluation of rock failure criteria constrained by polyaxial test data for five different rocks, *International Jour. Rock Mech. Min. Sci.*, 39, 695-729.
- 2002* Flemings, P., B.B. Stump, T. Finkbeiner and M.D. Zoback, Overpressure and flow-focusing in the South Eugene Island field (offshore Louisiana): Theory, examples and implications, *American Journal of Science*, 302, 827-855.
- 2002 Zoback, M.D. and M.L. Zoback, Stress in the Earth's Lithosphere, in *Encyclopedia of Physical Science and Technology*, Third Edition, Academic Press, 16, 143-154.
- 2002 Zoback, M.D., and M.L. Zoback, State of Stress in Earth's Lithosphere, *Handbook of Earthquake and Engineering Seismology*, ed. W.H.K. Lee, 81a, 559-568.
- 2002* Zoback, M.D., J. Townend and B. Grollimund, Steady-state failure equilibrium and deformation of intraplate lithosphere, *International Geological Review*, 44, 383-401.
- 2001* Chery, J., M.D. Zoback and R. Hassani, An integrated mechanical model of the San Andreas fault in central and northern California, *Jour. Geophys. Res.*, v. 106, pp. 22051-22061.
- 2001 Colmenares, L.B. and M.D. Zoback, Statistical evaluation of six rock failure criteria constrained by polyaxial test data, *Proc 38th U.S. Symposium on Rock Mechanics*, Wash. D.C., Balkema, Lisse, Netherlands, p. 1251-1258.
- 2001* Finkbeiner, T., M.D. Zoback, P. Flemings and B. Stump, Stress, pore pressure, and dynamically constrained hydrocarbon columns in the South Eugene Island 330 field, northern Gulf of Mexico, *AAPG Bulletin*, v. 85, no. 6, pp. 1007-1031.
- 2001* Grollimund, B. and M.D. Zoback. Did deglaciation trigger intraplate seismicity in the New Madrid seismic zone. *Geology*, v. 29, no. 2, pp. 175-178.
- 2001* Grollimund, B., M.D. Zoback, D.J. Wiprut, and L. Arnesen. Regional synthesis of stress orientation, pore pressure and least principal stress data in the Norwegian sector of the North Sea. *Petrol. Geoscience*, v. 7, pp. 173-180.
- 2001* Ito, T., M.D. Zoback and P. Peska, Utilization of mud weights in excess of the least principal stress to stabilized wellbores: Theory and practical examples, *Petroleum Engineers Drilling and Completions*, v. 16, pp. 221-229.
- 2001* M.D. Zoback, A.W. Chan and J.C. Zinke, Production-induced normal faulting, *Proc. 38th U.S. Symposium on Rock Mechanics*, Wash. D.C., Balkema, Lisse, Netherlands, p. 157-163.
- 2001 Townend, J. and M.D. Zoback, Focal mechanism stress inversions in southern California and the strength of the San Andreas fault, *Proc. 3rd Conference on Tectonic Problems of the San Andreas fault system*, Goetz Bokelmann and Robert Kovach, ed., Stanford university, p. 268-276.
- 2001* Townend, J. and M.D. Zoback. Implications of earthquake focal plane mechanisms for the frictional strength of the San Andreas fault. *Geological Society of London Spec. Pub.*, v. 186, pp. 13-21.
- 2001* Zoback, M.D. and B. Grollimund, Impact of deglaciation on present-day intraplate seismicity in eastern North America and western Europe, *Earth and Planetary Sciences*, v. 333, pp. 23-33.
- 2001* Zoback, M.D. and J. Townend. Implications of hydrostatic pore pressures and high crustal strength for the deformation of intraplate lithosphere. *Tectonophysics*, v. 336, pp. 19-30.
- 2001* Zoback, M.D. and J. Zinke, Production-induced normal faulting in the Valhall and Ekofisk oil fields, *Pure and Applied Geophysics*, v. 159, pp. 403-420.
- 2000* Grollimund, B. and M.D. Zoback. Post glacial lithospheric flexure and induced stresses and pore pressure changes in the northern North Sea. *Tectonophysics*, v. 327, pp. 61-81.
- 2000 Hickman, S.H., M.D. Zoback, C.A. Barton, R. Benoit, J. Svitek, and R. Summers. Stress and permeability heterogeneity within the Dixie Valley geothermal reservoir: recent results from well 82-5. *Proceedings, Twenty-fifth workshop on Geothermal Reservoir Engineering*, Stanford University, Jan. 24-26, SGP-TR-165.
- 2000* Ito, T. and M.D. Zoback. Fracture permeability and in situ stress to 7 km depth in the KTB scientific drillhole. *Geophys. Res. Lett.*, v. 27, pp. 1045-1048.
- 2000* Townend, J. and M.D. Zoback. How faulting keeps the crust strong. *Geology*, v. 28, no. 5, pp. 399-402.
- 2000* Wiprut, D. and M.D. Zoback. Constraining the full stress tensor in the Visund field, Norwegian North Sea: Application to wellbore stability and sand production. *Int'l. J. Rock Mech. & Mining Sci.*, v. 37, pp. 317-336, 2000.
- 2000* Wiprut, D. and M.D. Zoback. Fault reactivation and fluid flow along a previously dormant normal fault in the Norwegian North Sea. *Geology*, v. 28, no. 7, pp. 595-598.
- 2000* Zinke, J.C. and M.D. Zoback. Structure-related and stress-induced shear wave velocity anisotropy: Observations from microearthquakes near the Calaveras fault in central California. *Bull. Seis. Soc. Amer.*,

- v. 90, pp. 1305-1312.
- 2000 Zoback, M.D., Strength of the San Andreas. *Nature*, v. 405, pp. 31-32.
- 1999 Barton, C.A. and M.D. Zoback. Earth stress, rock fracture and wellbore failure - Wellbore imaging technologies applied to reservoir geomechanics and environmental engineering. In: *Proc. 4th SEG Japan International Symposium*, Dec. 1998, Tokyo, pp. 49-56.
- 1999* Brudy, M. and M.D. Zoback. Drilling-induced tensile wall-fractures: Implications for determination of in-situ stress orientation and magnitude. *Int'l. J. Rock Mech.*, v. 36, pp. 191-215.
- 1999 Ito, T., M.D. Zoback, and P. Peska. Utilization of mud weights in excess of the least principal stress in extreme drilling environments. In: *37th U.S. Rock Mechanics Symposium*, Vail Colorado, June 6-9, B. Amadei, R.L. Kranz, G.A. Scott, P.H. Smeallie, pp. 253-259, Balkema, Rotterdam.
- 1999* Lund, B. and M.D. Zoback. State of stress to 7 km depth in the Siljan drill holes from observations of drilling-induced tensile wall fractures. *Int'l. J. Rock Mech.*, v. 36, pp. 169-190.
- 1999 Willson, S., N.C. Last, M.D. Zoback, and D. Moos. Drilling in South America: A wellbore stability approach for complex geologic conditions, SPE 53940. In: *1999 SPE Latin American and Caribbean Petroleum Engineering Conference*, Caracas, Venezuela 21-23 April.
- 1998 Barton, C., S. Hickman, R. Morin, M.D. Zoback, and D. Benoit. Reservoir scale fracture permeability in the Dixie Valley, Nevada geothermal field. *SPE/ISRM Rock Mechanics in Petroleum Engineering*, Soc. of Petroleum Eng., Richardson, TX., SPE 47371, pp. 315-322.
- 1998 Chang, C. and M.D. Zoback. Viscous rheology and the state of stress in unconsolidated sands. *SPE/ISRM Rock Mechanics in Petroleum Engineering*, Soc. of Petroleum Eng., Richardson, TX., pp. 465-474.
- 1998* Dholakia, S.K., A. Aydin, D. Pollard, and M.D. Zoback. Development of fault-controlled hydrocarbon migration pathways in the Monterey formation, California. *AAPG Bull.*, v. 82, pp. 1551-1574.
- 1998 Finkbeiner, T. and M.D. Zoback. In-situ stress and pore pressure in the South Eugene Island field, Gulf of Mexico. *SPE/ISRM Rock Mechanics in Petroleum Engineering*, Soc. of Petroleum Eng., Richardson, TX., pp. 69-78.
- 1998 Grollmund, B., M.D. Zoback, and L. Arneson. Flexurally-induced stresses in the northern North Sea: preliminary comparison of observation and theory. *SPE/ISRM Rock Mechanics in Petroleum Engineering*, Soc. of Petroleum Eng., Richardson, TX., SPE 47243, pp. 189-198.
- 1998 Hickman, S., M.D. Zoback, and R. Benoit. Tectonic controls on fault-zone permeability in a geothermal reservoir at Dixie Valley, Nevada. *SPE/ISRM Rock Mechanics in Petroleum Engineering*, Soc. of Petroleum Eng., Richardson, TX., pp. 79-88.
- 1998 Moos, D., P. Peska, and M.D. Zoback. Predicting the stability of horizontal wells and multi-laterals- the role of in situ stress and rock properties. *SPE International Conference on Horizontal Well Technology*, Calgary, Alberta, Canada, Soc. of Petroleum Eng., Richardson, TX., SPE 50386, pp. 315-322.
- 1998 Peska, P. and M.D. Zoback. Drilling-induced tensile fractures: formation and constraints on the full stress tensor. In *""Mechanics of Jointed and Faulted Rock,"" eds., H.P. Rossmanith, A.A. Balkema, Brookfield, Vermont, pp. 331-337.*
- 1998 Wiprut, D. and M.D. Zoback. High horizontal stress in the Visund field, Norwegian North Sea: Consequences for borehole stability and sand production. *SPE/ISRM Rock Mechanics in Petroleum Engineering*, Soc. of Petroleum Eng., Richardson, TX., pp. 199-208.
- 1997 Moos, D., M.D. Zoback, and L. Bailey. Feasibility study of the stability of openhole multilaterals, Cook inlet, Alaska. In: *SPE Mid-Continent Operations Symposium held in Oklahoma City, Oklahoma, 28-31 March*, Soc. of Petroleum Eng., Richardson, TX., SPE 52186.
- 1996* See a list of Mark's prior Publications