11:00-20:00 CLOSED SESSION—COMMITTEE AND STAFF ONLY

DAY TWO

07:45-13:00 CLOSED SESSION—COMMITTEE AND STAFF ONLY

End of meeting

MEETING 5

Denver, CO, January 10-11, 2012

CLOSED SESSIONS—COMMITTEE AND STAFF ONLY

APPENDIX C

Observations of Induced Seismicity

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Akmaar	Netherlands	3.5	Oil and gas extraction	Giardini (2011)
Akosombo	Ghana	5.3	Surface water reservoir	Guha (2000)
Apollo Hendrick Field, Texas	USA	2	Secondary recovery	Doser et al. (1992)
Ashtabula, Ohio	USA	3.6	Wastewater injection	Armbruster et al. (1987)
Assen	Netherlands	2.8	Oil and gas extraction	Grasso (1992)
Aswan	Egypt	5.6	Surface water reservoir	Guha (2000)
Attica, New York	USA	5.2	Other	Nicholson and Wesson (1992)
Bad Urach	Germany	1.8	Geothermal	Evans et al. (2012)
Bajina Basta	Yugoslavia	4.8	Surface water reservoir	Guha (2000)
Barsa-Gelmes-Wishka Oilfield	Turkmenistan	6	Secondary recovery	Kouznetsov et al. (1994)
Basel	Switzerland	3.4	Geothermal	Giardini (2011)
Belchalow	Poland	4.6	Other	Giardini (2011)
Benmore	New Zealand	5	Surface water reservoir	Guha (2000)
Bergermeer Field	Netherlands	3.5	Oil and gas extraction	van Eck et al. (2006)
Berlin	El Salvador	4.4	Geothermal	Bommer et al. (2006)
Bhatsa	India	4.8	Surface water reservoir	Guha (2000)
Blackpool	UK	2.3	Hydraulic fracturing	de Pater and Baisch (2011)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Cajuru, Brazil	Brazil	4.7	Surface water reservoir	Guha (2000)
Camarillas, Spain	Spain	4.1	Surface water reservoir	Guha (2000)
Canelles, Spain	Spain	4.7	Surface water reservoir	Guha (2000)
Catoosa, Oklahoma[1]	USA	4.7	Oil and gas extraction	Nicholson and Wesson (1992)
Cesano	Italy	2	Geothermal	Evans et al. (2012)
Charvak	Uzbekistan	4	Surface water reservoir	Guha (2000)
Clark Hill	USA	4.3	Surface water reservoir	Guha (2000)
Cleburne, Texas	USA	2.8	Oil and gas extraction	Howe et al. (2010)
Cleveland, Ohio[2]	USA	3	Other	Nicholson and Wesson (1992)
Coalinga, California	USA	6.5	Oil and gas extraction	McGarr (1991)
Cogdell Canyon Reef, Texas	USA	4.6	Secondary recovery	Davis and Pennington (1989); Nicholson and Wesson (1990)
Cold Lake, Alberta	Canada	2	Secondary recovery	Nicholson and Wesson (1990)
Cooper Basin	Australia	3.7	Geothermal	Majer et al. (2007)
Coso, California	USA	2.6	Geothermal	Julian et al. (2007); Foulger et al. (2008)
Coyote Valley	USA	5.2	Surface water reservoir	Guha (2000)
Dale, New York	USA	1	Other	Nicholson and Wesson (1990)
Dallas Fort Worth, Texas	USA	3.3	Wastewater injection	Frohlich et al. (2010)
Dan	Denmark	4	Oil and gas extraction	Grasso (1992)
Danjiangkou	China	4.7	Surface water reservoir	Guha (2000)
Denver, Colorado[3]	USA	4.8	Wastewater injection	Hermann et al. (1981)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Desert Peak, Nevada	USA	0.74	Geothermal	Chabora et al. (2012)
Dhamni	India	3.8	Surface water reservoir	Guha (2000)
Dollarhide, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1992)
Dora Roberts, Texas	USA	3	Secondary recovery	Nicholson and Wesson (1992)
East Durant, Oklahoma	USA	3.5	Oil and gas extraction	Nicholson and Wesson (1992)
East Texas, Texas	USA	4.3	Secondary recovery	Nicholson and Wesson (1992)
Ekofisk	Norway	3.4	Oil and gas extraction	Grasso (1992)
El Dorado, Arkansas	USA	3	Wastewater injection	Cox (1991)
El Reno, Oklahoma[4]	USA	5.2	Oil and gas extraction	Nicholson and Wesson (1992)
Eola field, Oklahoma	USA	2.8	Hydraulic fracturing	Holland (2011)
Eucumbene	Australia	5	Surface water reservoir	Guha (2000)
Fashing, Texas	USA	3.4	Oil and gas extraction	Pennington et al. (1986)
Fenton Hill, New Mexico	USA	1	Geothermal	Nicholson and Wesson (1992)
Fjallbacka	Sweden	–0.2	Geothermal	Evans et al. (2012)
Fort St. John, British Columbia	Canada	4.3	Secondary recovery	Horner et al. (1994)
Foziling	China	4.5	Surface water reservoir	Guha (2000)
Gazli	Uzbekistan	7.3	Oil and gas extraction	Adushkin et al. (2000)
Geysers, California	USA	4.6	Geothermal	Majer et al. (2007)
Gobles Field, Ontario	Canada	2.8	Secondary recovery	Nicholson and Wesson (1990)
Goose Creek, Texas	USA	unknown[5]	Oil and gas extraction	Nicholson and Wesson (1992)
Grandval	France	unknown[6]	Surface water reservoir	Guha (2000)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Groningen Field	Netherlands	3	Oil and gas extraction	van Eck et al. (2006)
Gross Schonebeck	Germany	−1.1	Geothermal	Evans et al. (2012)
Grozny	Caucasus (Russia)	3.2	Oil and gas extraction	Guha (2000)
Gudermes	Caucasus (Russia)	4.5	Oil and gas extraction	Smirnova (1968)
Guy and Greenbrier, Arkansas	USA	4.7	Wastewater injection	Horton (2012)
Harz	Germany	3.5	Other	Giardini (2011)
Hellisheidi	Iceland	2.4	Geothermal	Evans et al. (2012)
Hijiori	Japan	0.3	Geothermal	Kaieda et al. (2010)
Hoover	USA	5	Surface water reservoir	Guha (2000)
Horstberg	Germany	0	Geothermal	Evans et al. (2012)
Hsinfengchiang	China	6.1	Surface water reservoir	Guha (2000)
Hunt Field, Mississippi[7]	USA	3.6	Secondary recovery	Nicholson and Wesson (1992)
Idukki	India	3.5	Surface water reservoir	Guha (2000)
Imogene Field, Texas	USA	3.9	Oil and gas extraction	Pennington et al. (1986)
Inglewood Oil Field, California	USA	3.7	Secondary recovery	Nicholson and Wesson (1992)
Ingouri	Caucasus (Russia)	4.4	Surface water reservoir	Guha (2000)
Itizhitezhi	Zambia	4.2	Surface water reservoir	Guha (2000)
Kariba	Zambia	6.2	Surface water reservoir	Guha (2000)
Kastraki	Greece	4.6	Surface water reservoir	Guha (2000)
Kermit Field, Texas	USA	4	Secondary recovery	Nicholson and Wesson (1990)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Kerr	USA	4.9	Surface water reservoir	Guha (2000)
Kettleman North, California	USA	6.1	Oil and gas extraction	McGarr (1991)
Keystone I Field, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1990)
Keystone II Field, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1990)
Kinnersani	India	5.3	Surface water reservoir	Guha (2000)
Koyna	India	6.5	Surface water reservoir	Guha (2000)
Krafla	Iceland	2	Geothermal	Evans et al. (2012)
Kremasta	Greece	6.3	Surface water reservoir	Guha (2000)
German Continental Deep Drilling Program	Germany	1.2	Geothermal	Evans et al. (2012)
Kurobe	Japan	4.9	Surface water reservoir	Guha (2000)
Kuwait	Kuwait	4.7	Oil and gas extraction	Bou-Rabee (1994)
Lacq	France	4.2	Oil and gas extraction	Grasso and Wittlinger (1990)
Lake Charles, Louisiana[8]	USA	3.8	Oil and gas extraction	Nicholson and Wesson (1990)
Lambert Field, Texas	USA	3.4	Secondary recovery	Nicholson and Wesson (1992)
Landau	Germany	2.7	Geothermal	Evans et al. (2012)
Larderello-Travale	Italy	3	Geothermal	Evans et al. (2012)
Latera	Italy	2.9	Geothermal	Evans et al. (2012)
LGDD	Russia	4.2	Other	Giardini (2011)
Love County, Oklahoma[9]	USA	2.8	Secondary recovery	Nicholson and Wesson (1990)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Love County, Oklahoma	USA	1.9	Oil and gas extraction (hydraulic fracturing for conventional oil and gas development)	Nicholson and Wesson (1990)
Manicouagan	Canada	4.1	Surface water reservoir	Guha (2000)
Marathon	Greece	5.7	Surface water reservoir	Guha (2000)
Matsushiro	Japan	2.8	Wastewater injection	Ohtake (1974)
Mica, Canada	Canada	4.1	Surface water reservoir	Guha (2000)
Monahans, Texas	USA	3	Secondary recovery	Nicholson and Wesson (1992)
Monte Amiata	Italy	3.5	Geothermal	Evans et al. (2012)
Montebello, California	USA	5.9	Oil and gas extraction	Nicholson and Wesson (1992)
Montecillo, South Carolina	USA	2.8	Surface water reservoir	Guha (2000)
Monteynard	France	4.9	Surface water reservoir	Guha (2000)
Mutnovsky, Kamchatka	Russia	2	Geothermal	Kugaenko et al. (2005)
Northern Panhandle, Texas	USA	3.4	Secondary recovery	Nicholson and Wesson (1990)
Nurek	Tadjikstan	4.6	Surface water reservoir	Guha (2000)
Ogachi	Japan	2	Geothermal	Kaieda et al. (2010)
Petroleum field	Oman	2.1	Oil and gas extraction	Sze (2005)
Orcutt Field, California	USA	3.5	Oil and gas extraction	Nicholson and Wesson (1992)
Oroville, California	USA	5.7	Surface water reservoir	Guha (2000)
Paradise Valley, Colorado	USA	0.8	Wastewater injection	Nicholson and Wesson (1992)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Paradox Valley, Colorado	USA	4.3	Wastewater injection	Ake et al. (2005)
Perry, Ohio	USA	2.7	Wastewater injection	Nicholson and Wesson (1992)
Piastra	Italy	4.4	Surface water reservoir	Guha (2000)
Pieve de Cadore	Italy	4.3	Surface water reservoir	Guha (2000)
Porto Colombia	Brazil	5.1	Surface water reservoir	Guha (2000)
Rangely, Colorado	USA	3.1	Secondary recovery	Nicholson and Wesson (1990)
Renqiu oil field	China	4.5	Secondary recovery	Genmo et al. (1995)
Richland County, Illinois[10]	USA	4.9	Oil and gas extraction	Nicholson and Wesson (1992)
Rocky Mountain House, Alberta	Canada	3.4	Oil and gas extraction	Wetmiller (1986)
Romashkino, Tartarstan	Russia	4	Secondary recovery	Adushkin et al. (2000)
Rongchang, Chongqing	China	5.2	Oil and gas extraction	Lei et al. (2008)
Rosemanowes,	UK	2	Geothermal	Evans et al. (2012)
Roswinkel Field	Netherlands	3.4	Oil and gas extraction	van Eck et al. (2006)
Rotenburg	Germany	4.5	Oil and gas extraction	Giardini (2011)
Sefia Rud	Iran	4.7	Surface water reservoir	Guha (2000)
Shandong	China	2.4	Secondary recovery	Shouzhong et al. (1987)
Shenwo	China	4.8	Surface water reservoir	Guha (2000)
Sleepy Hollow, Nebraska	USA	2.9	Oil and gas extraction	Rothe and Lui (1983)
Snipe Lake	Canada	5.1	Secondary recovery	Nicholson and Wesson (1992)
Soultz	France	2.9	Geothermal	Evans et al. (2012)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
South-central Texas	USA	4.3	Oil and gas extraction	Davis et al. (1995)
Southern Alabama	USA	4.9	Secondary recovery	Gomberg and Wolf (1999)
Sriramsagar	India	3.2	Surface water reservoir	Guha (2000)
Starogroznenskoe Oilfield	Russia	4.7	Oil and gas extraction	Kouznetsov et al. (1994)
Strachan, Alberta	Canada	3.4	Oil and gas extraction	Grasso (1992)
Southwest of Elsenbach	Germany	5.8	Other	Giardini (2011)
Tomahawk Field, New Mexico	USA	Unknown[11]	Wastewater injection	Nicholson and Wesson (1992)
Torre Alfina	Italy	3	Geothermal	Evans et al. (2012)
Unterhaching	Germany	2.4	Geothermal	Evans et al. (2012)
Upper Silesian	Poland	4.45	Other	Giardini (2011)
Vajont	Italy	3	Surface water reservoir	Guha (2000)
Valhall and Ekofisk Oilfields	Norway	Unknown[12]	Secondary recovery	Zoback and Zinke (2002)
Varragamba	Australia	5.4	Surface water reservoir	Guha (2000)
Vogtland	Germany		Wastewater injection	Baisch et al. (2002)
Vouglans	France	4.4	Surface water reservoir	Guha (2000)
War Wink Field, Texas	USA	2.9	Oil and gas extraction	Doser et al. (1992)
Ward-Estes Field, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1992)
Ward-South Field, Texas	USA	3	Secondary recovery	Nicholson and Wesson (1992)
West Texas	USA	3.1	Oil and gas extraction	Keller et al. (1987)
Whittier Narrows, California	USA	5.9	Oil and gas extraction	McGarr (1991)

Site/City/State	Country	Max Magnitude	Technology Type (causing induced seismicity)	Reference
Wilmington Field, California	USA	3.3	Oil and gas extraction	Kovach (1974)

NOTE: "Other" refers to, e.g., coal and solution mining.

[1] Nicholson and Wesson (1990, 1992) were not able to confirm that the cause of the earthquake was oil and gas extraction; waterflooding and waste disposal were also active in the area at the time.

[2] Nicholson and Wesson (1990, 1992) were not able to confirm the accuracy of the maximum magnitude of this event, which occurred at the turn of the 20th century (1898-1907).

[3] For the Denver earthquakes of 1967-1968, Healy et al. (1968) reported magnitudes up to **M** 5.3 on an unspecified scale that were derived from local instruments.

[4] Nicholson and Wesson (1992) were not able to confirm conclusively that the earthquake was caused by oil and gas extraction.

[5] Nicholson and Wesson (1992) were not able to confirm conclusively that the earthquake was caused by oil extraction or the magnitudes of the events that occurred in the 1920s. Note that this location is not plotted in the figures (maps) in Chapter 1.

[6] Guha (2000) describes the earthquake using Modified Mercalli Intensity (V), but does not indicate moment magnitude.

[7] Nicholson and Wesson (1990, 1992) were not able to confirm conclusively that the event(s) were due to waterflooding for secondary recovery.

[8] Nicholson and Wesson (1990) were not able to confirm conclusively that the event(s) were due to oil and gas extraction activities.

[9] Nicholson and Wesson (1990) were not able to confirm the maximum magnitude of the events at this site.

[10] Nicholson and Wesson (1990, 1992) were not able to confirm conclusively that the event(s) were due to oil extraction.

[11] Nicholson and Wesson (1992) were not able to confirm the maximum magnitude of the events at this site.

[12] Zoback and Zinke (2002) did not provide a maximum magnitude, although the events recorded and analyzed are described as "microseismic" events.

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APPENDIX C

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APPENDIX D

Letters between Senator Bingaman and Secretary Chu

Exec-2010-010389

United States Senate
COMMITTEE ON
ENERGY AND NATURAL RESOURCES
WASHINGTON, DC 20510-6150

ENERGY.SENATE.GOV

June 17, 2010

The Honorable Steven Chu
Secretary of Energy
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Mr. Secretary:

Many of the next generation energy technologies vital for our country's future require the injecting of fluids – be they water, carbon dioxide, or other mixes – deep into the earth's subsurface. Geothermal energy extraction, geologic carbon sequestration, hydraulic fracturing to extract natural gas from shales, and enhanced oil recovery all require the injection and movement of fluids deep underground, a process that by its very nature may induce seismic activity. I understand that the Department of Energy has recently initiated studies in several of its offices and programs to address the issue of induced seismicity, and I commend those efforts.

I am writing to ask that the Department of Energy, in cooperation with the Department of the Interior and all other relevant agencies, initiate a comprehensive and independent National Academy of Sciences and the National Academy of Engineering study to examine the possible scale, scope, and consequences of seismicity induced by energy technologies. Though oil and natural gas extraction processes have moved fluids through the ground for many decades without significant seismic consequences, the prospect of greatly increased deployment of these new energy technologies in the coming years, coupled with a commensurate rising public concern about their safety, makes it necessary to now better understand the nature and scale of seismicity that may be induced by all subsurface energy activity.

APPENDIX D

Recent studies such as the 2010 joint University of Texas – Southern Methodist University article by Cliff Frohlich et al. regarding the correlations of seismic activity with natural gas extraction activities in Texas, and the 2007 study led by Ernest L. Majer of the Lawrence Berkeley National Laboratory entitled, "Induced Seismicity Associated with Enhanced Geothermal Systems," indicate a possible link between energy-related subsurface fluid movement and increased seismic activity. Importantly, both studies found that all recorded earthquakes that may have been induced by energy projects were small (less than 4.6 on the Richter scale) and had few or no significant impacts on human health or property. However, both studies emphasize that a more extensive, thorough, and definitive study is necessary to fill gaps in existing knowledge, such as how subsurface energy activities interact with existing geologic stresses to increase or decrease the risk of induced seismic events.

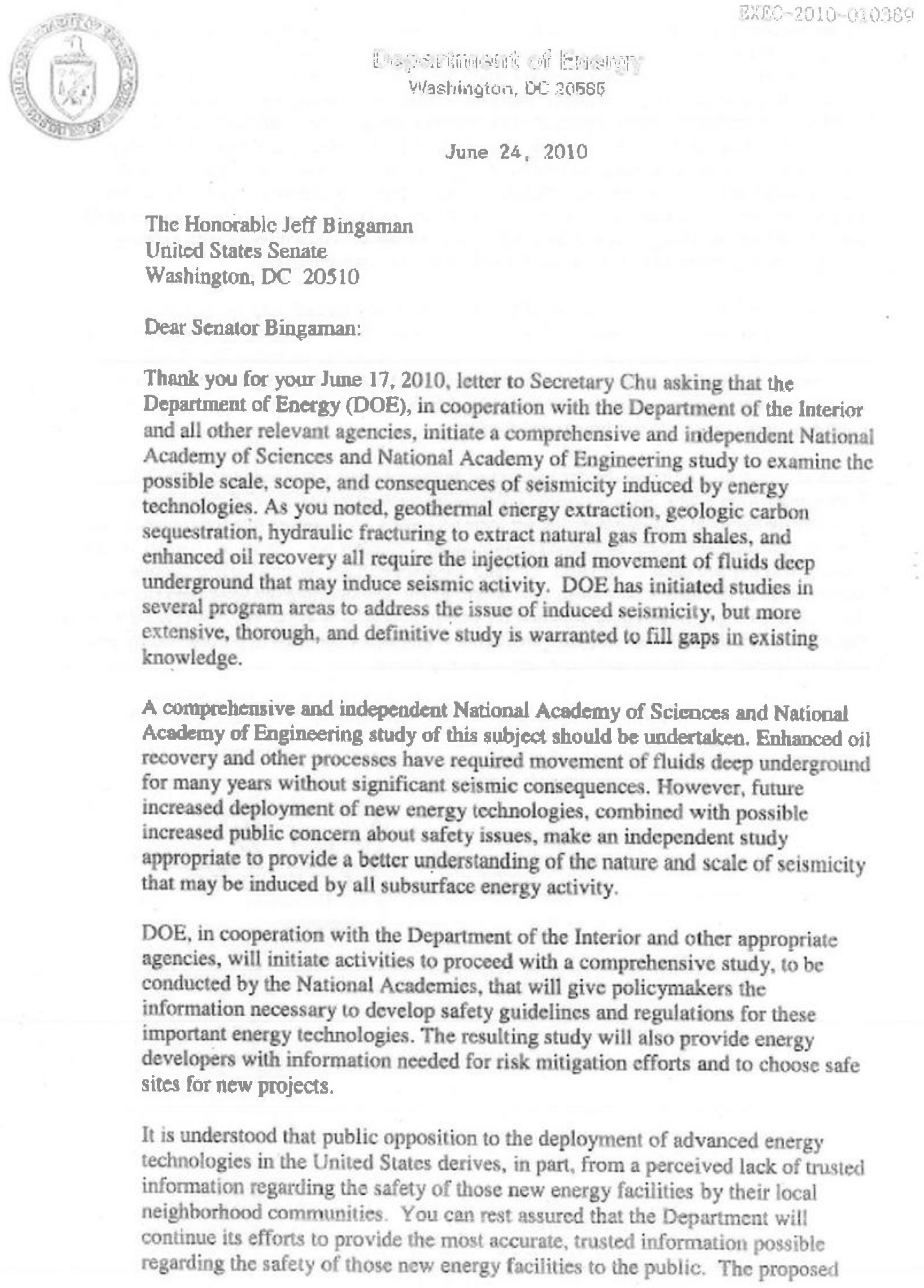
Such a comprehensive study – conducted by the scientifically trusted, nationally recognized, and independent National Academies – will give policymakers the information they need to develop better safety guidelines and regulations for these important energy technologies. It will also provide energy developers with tools to implement appropriate risk mitigation efforts and to choose safe sites for new projects, and arm the public with the information they need to be confident in the safety of their homes and families.

Much of public opposition to the deployment of advanced energy technologies in the United States stems from a lack of clear, trusted information regarding the safety of those new energy facilities for the local communities that are their neighbors. A National Academies study can provide information to these concerned communities – whether near a new geothermal facility tapping heat trapped deep in the earth, a carbon sequestration site storing carbon dioxide underground to facilitate a new clean coal future, a drill rig extracting the newfound riches of America's shale gas, or an aging domestic oil well rejuvenated by enhanced recovery techniques that replaces foreign oil with domestic production – and allow America to proceed safely and with confidence to a cleaner and more secure energy future.

I appreciate your consideration of this request, and look forward to working with you on this.

Sincerely,

Jeff Bingaman
Chairman



EXEC-2010-010369

Department of Energy
Washington, DC 20585

June 24, 2010

The Honorable Jeff Bingaman
United States Senate
Washington, DC 20510

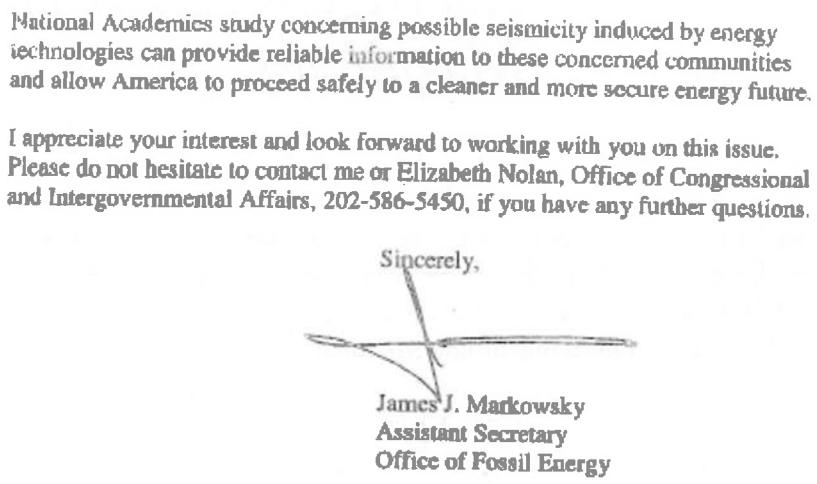
Dear Senator Bingaman:

Thank you for your June 17, 2010, letter to Secretary Chu asking that the Department of Energy (DOE), in cooperation with the Department of the Interior and all other relevant agencies, initiate a comprehensive and independent National Academy of Sciences and National Academy of Engineering study to examine the possible scale, scope, and consequences of seismicity induced by energy technologies. As you noted, geothermal energy extraction, geologic carbon sequestration, hydraulic fracturing to extract natural gas from shales, and enhanced oil recovery all require the injection and movement of fluids deep underground that may induce seismic activity. DOE has initiated studies in several program areas to address the issue of induced seismicity, but more extensive, thorough, and definitive study is warranted to fill gaps in existing knowledge.

A comprehensive and independent National Academy of Sciences and National Academy of Engineering study of this subject should be undertaken. Enhanced oil recovery and other processes have required movement of fluids deep underground for many years without significant seismic consequences. However, future increased deployment of new energy technologies, combined with possible increased public concern about safety issues, make an independent study appropriate to provide a better understanding of the nature and scale of seismicity that may be induced by all subsurface energy activity.

DOE, in cooperation with the Department of the Interior and other appropriate agencies, will initiate activities to proceed with a comprehensive study, to be conducted by the National Academies, that will give policymakers the information necessary to develop safety guidelines and regulations for these important energy technologies. The resulting study will also provide energy developers with information needed for risk mitigation efforts and to choose safe sites for new projects.

It is understood that public opposition to the deployment of advanced energy technologies in the United States derives, in part, from a perceived lack of trusted information regarding the safety of those new energy facilities by their local neighborhood communities. You can rest assured that the Department will continue its efforts to provide the most accurate, trusted information possible regarding the safety of those new energy facilities to the public. The proposed



National Academics study concerning possible seismicity induced by energy technologies can provide reliable information to these concerned communities and allow America to proceed safely to a cleaner and more secure energy future.

I appreciate your interest and look forward to working with you on this issue. Please do not hesitate to contact me or Elizabeth Nolan, Office of Congressional and Intergovernmental Affairs, 202-586-5450, if you have any further questions.

Sincerely,

James J. Markowsky
Assistant Secretary
Office of Fossil Energy

APPENDIX E

Earthquake Size Estimates and Negative Earthquake Magnitudes

The original and arguably the best-known magnitude scale for measuring the size of an earthquake is the Richter scale, derived by Charles Richter in 1935 at the California Institute of Technology to measure earthquake size in Southern California. Using an early seismograph he defined local magnitude M_L to be

$$M_L = \mathrm{Log}A - \mathrm{Log}A_o$$

where A is the maximum amplitude of deflection of a needle on a chart, in millimeters, measured on the seismograph. A_o is an empirical distance correction appropriate for the region (Richter, 1936). Richter assigned a magnitude 3 to an event with amplitude of 1 mm recorded on a Wood Anderson seismograph at 100 km distance from the source, and a magnitude 0 with amplitude 0.001 mm at 100 km, thought to be the smallest possible instrumentally recorded earthquake (Shemeta, 2010).

Since the 1930s advancements in equipment design such as more sensitive geophones and digital recording equipment and closer proximity to earthquake sources dramatically advanced the ability to record and analyze data from small earthquakes. Using borehole seismic arrays located within a few hundred meters of an earthquake source, very small earthquakes can be recorded. These events are smaller than the baseline magnitude of "0" originally designed by Richter, therefore the range of event sizes continues into the negative magnitude range (Figure E.1).

Because the Richter scale was designed for the Wood Anderson seismograph measurements, its routine use in modern seismology is now quite limited; however, most modern earthquake magnitudes are based on scales that relate back to the Richter scale.

OTHER SIZE ESTIMATES FOR EARTHQUAKES

In practice Richter's method for estimating earthquake magnitude has been largely supplanted by other more flexible and robust measures of magnitude. The moment magnitude, which is scaled to agree with the Richter magnitude, is in wide use because it can be

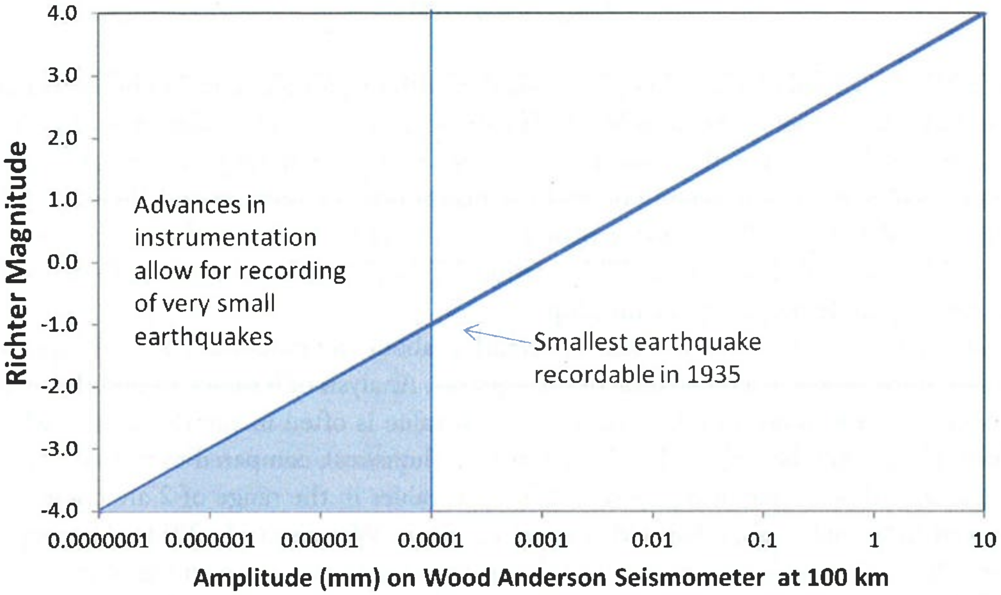


FIGURE E.1 A plot of measured earthquake amplitude versus magnitude. The more sensitive the seismic instruments, the smaller the measureable magnitude, reaching into the negative magnitude range.

tied to other direct measures of the size of an earthquake. The seismic moment is a routine measurement describing the strength of an earthquake and is defined as

$$M_o = \mu S d$$

where **μ** is the shear modulus, **S** is the surface area of the fault, and **d** is the average displacement along the fault. The moment magnitude, M_w, is related to seismic moment by the Hanks and Kanamori (1979) equation

$$M_w = {}^2/_3 \, \mathrm{Log} M_o - 6$$

where M_o is in Newton meters, valid for earthquakes ranging from magnitude 3 to 7 (Shemeta, 2010). There are a variety of methods used to calculate a seismic moment from microseismic waveforms.

EARTHQUAKE "B VALUES"

Small earthquakes occur much more often than large earthquakes. The number of earthquakes with respect to magnitude follows a power law distribution and is described by

$$\mathrm{Log}_{10}\mathbf{N} = \mathbf{a} - \mathbf{bM}$$

where **N** is the cumulative number of earthquakes with magnitudes equal to or larger than **M**, and **a** is the number of events of **M** = 0. The variable **b** describes the relationship between the number of large and small events and is the slope of the best-fit line between the number of earthquakes at a given magnitude and the magnitude (Gutenberg and Richter, 1944; Ishimoto and Iida, 1939). A **b** value close to 1.0 is commonly observed in many parts of the world for tectonic earthquakes. This relationship is often referred to as the Gutenberg-Richter magnitude frequency relationship.

Differences in the slope **b** reveal information about the potential size and expected number of the events in a population of earthquakes. Analysis of **b** values around the world has shown that in fluid injection scenarios the **b** value is often in the range of 2, which reflects a larger number of small events (swarm earthquakes), compared to tectonic earthquakes. In hydraulic fracturing microseismicity, **b** values in the range of 2 are commonly observed (Maxwell et al., 2008; Urbancic et al., 2010; Wessels et al., 2011). The high **b** values observed in hydraulic fracturing are thought to represent the opening of numerous small natural fractures during the high-pressure injection (Figure E.2). It is possible for a hydraulic fracture to grow into a nearby fault and reactivate it, if the orientation of the fault is favorable for slip under the current stress conditions in the reservoir. Figure E.3 is an example of a hydraulic fracture reactivating a small fault during injection.

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APPENDIX E

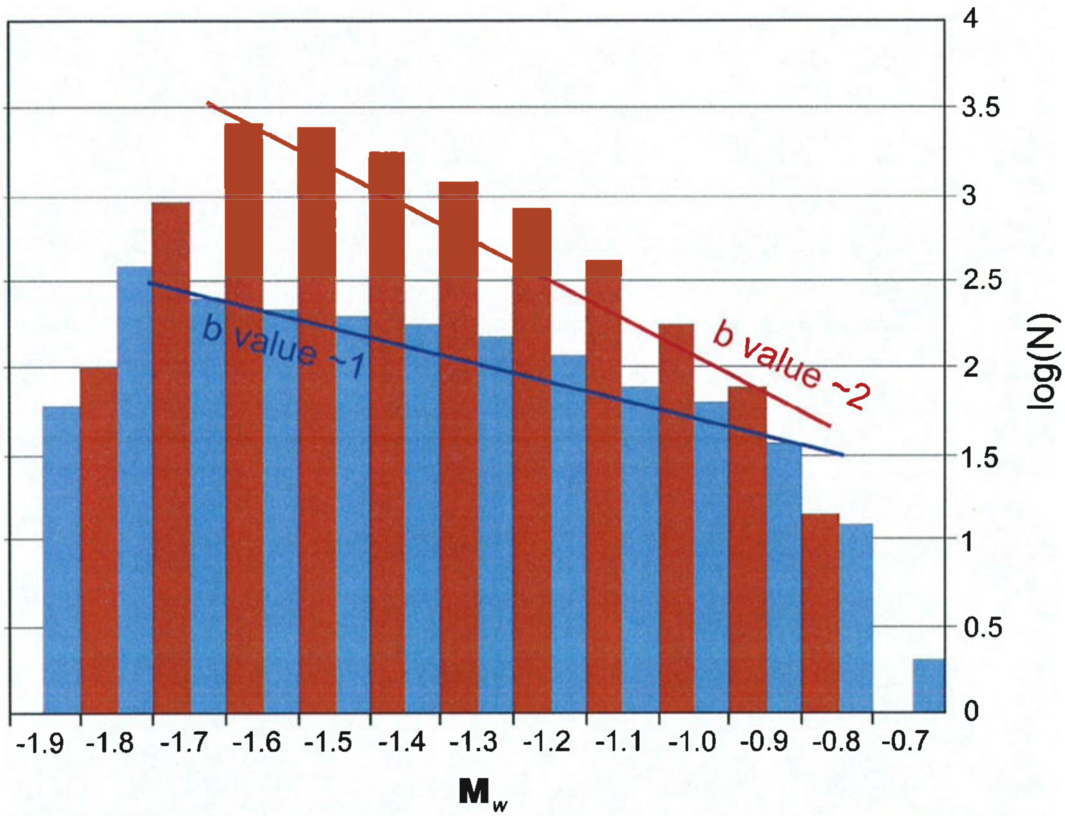

FIGURE E.2 Graph shows b values for two different microearthquake populations during a hydraulic fracture treatment. The b values vary from about 1 for reactivated tectonic microseismic events and 2 for microseismicity associated with the hydraulic fracture injection. The hydraulic fracture microseismic magnitudes are typically very small (less than **M** 0), hence the lack of larger microseismic events on this b value example. SOURCE: From Wessels et al. (2011).

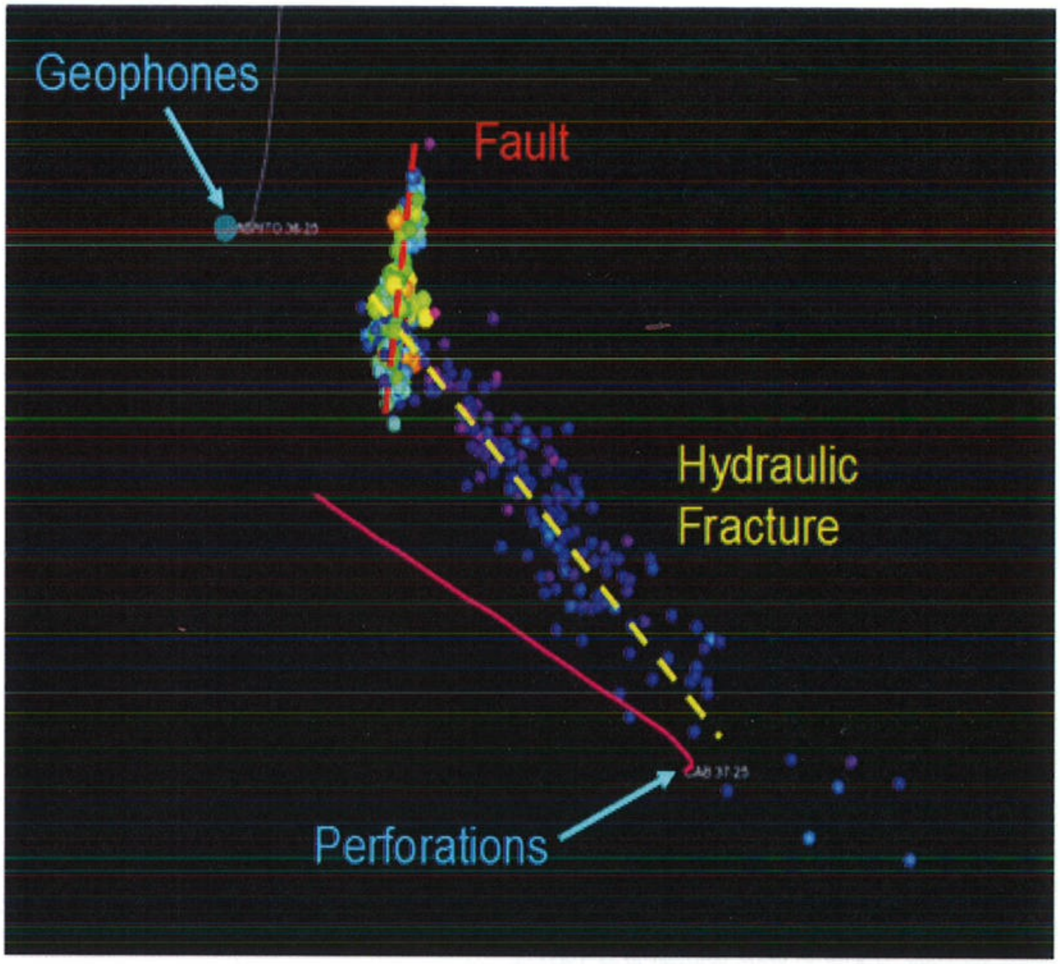

FIGURE E.3 Example of a reactivated fault during hydraulic fracturing. The figure is a map view of a microseismicity (colored spheres which are colored by magnitude; cool colors are small events) during a hydraulic fracture treatment. The fracturing well is shown by the pink line and is deviated away from a central wellhead location and extends vertically through the reservoir section; the injection location is labeled "Perforations." The data were recorded and analyzed using borehole receivers (marked Geophones). The blue dots show the growth of the hydraulic fracture to the northwest, then intersecting and reactivating a small fault in the reservoir, shown by change in fracture orientation and larger magnitude events (yellow dots). SOURCE: From Maxwell et al. (2008).

APPENDIX F

The Failure of the Baldwin Hills Reservoir Dam

On December 14, 1963, the dam built to contain the Baldwin Hill Reservoir located in southwest Los Angeles failed, releasing 250 million gallons of water into the housing subdivisions below the dam. Approximately 277 homes were damaged or destroyed and five people were killed by the disaster (Hamilton and Meehan, 1971). Although there is speculation that waterflooding operations in the Inglewood Oil Field (located to the west and south of the reservoir) were partially to blame for the failure of the reservoir dam, the dam itself did not fail due to an induced earthquake. Records from the Seismographic Laboratory of the California Institute of Technology located 15 miles northeast of the reservoir showed no earthquakes large enough to cause internal damage to the reservoir during the period 1950-1963 (Jansen, 1988). Instead, the sealing layers in the floor of the reservoir failed due to the "creep" of several geologic fractures below the reservoir, which caused the release of water through the floor of the reservoir that resulted in the structural failure of the dam itself.

The Baldwin Hills Reservoir was constructed between 1947 and 1951 by the Los Angeles Department of Water and Power. The reservoir was constructed on a hilltop and was formed by a dam on the north side and earthen dikes on the other three sides, which were constructed of materials excavated from the reservoir bowl. The soil under the reservoir was composed of porous material and was bisected by three known geologic faults (Jansen, 1988). The floor of the reservoir was made watertight by the use of two layers of asphalt with compacted earth between them. Below the upper layer of asphalt and earth, a level of pea gravel with tile drains was installed to allow the monitoring of leakage from the bottom of the reservoir. Extensive discharge from the drainage system was recorded during the initial filling of the reservoir, and filling was discontinued until repairs to the reservoir could be made (Jansen, 1988). Cracking in concrete portions of the reservoir was noted as early as 1951.

The Inglewood Oil Field was discovered in 1924 and covered approximately 1,200 acres when fully developed. At the time of the failure of Baldwin Hills Dam in 1963, the field had more than 600 producing wells, and the closest wells were located within 700 feet of the reservoir structure. The oil reservoir is divided into multiple compartments due to a series of geologic faults. Several of these faults not only divide the Inglewood Oil Field but also continue to the surface and are present on the site of the Baldwin Hills Reservoir. The depth of the wells in the Inglewood Field is between 2,000 and 4,000 feet. Due to subsurface fluid withdrawal, the ground level above the field exhibited a surface subsidence of approximately

10 feet by 1964. In order to increase production, waterflooding operations were commenced in 1954 and expanded in 1955 and 1961. These injection operations increased pore pressure in portions of the oil field from 50 psi to over 850 psi by 1963 (Hamilton and Meehan, 1971). Injection depths were as shallow as 1,200 feet.

The dam structure failed due to subsurface leakage of reservoir water beneath the floor of the impoundment and under the foundation of the dam itself. The subsurface leakage was caused by a cracked seal extending across the floor of the reservoir in line with the breach in the dam (Jansen, 1988). Movement of the geologic faults crossing the floor of the reservoir with downward displacement of 2 to 7 inches on the western side of several faults caused cracking in the asphalt membrane seal and allowed water to enter the porous soil beneath the dam. Later excavations of the bottom of the reservoir indicated that leakage had occurred for an appreciable amount of time before the dam failure. The slow movement of the faults beneath the reservoir has been attributed to (1) natural causes inherent in the geologic setting, (2) subsidence of the ground surface caused by oil and gas operations or by the filling of the reservoir with water, or (3) pressure injection of water in the Inglewood Field at shallow depths for oil and gas operations and in the presence of a fault system.

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APPENDIX G

Seismic Event Due to Fluid Injection or Withdrawal

To initiate a seismic event by activation of an existing fault, a critical condition involving the in situ state of stress and the pore pressure needs to be met. As discussed below, this condition stems, at least for the simplest case of slip initiation along a preexisting fault, from a combination of two fundamental concepts: (1) slip is initiated when the shear stress acting on the fault overcomes the frictional resistance and (2) the frictional resistance is given by the product of the friction coefficient times the normal effective stress, defined as the normal stress across the fault reduced by the fluid pressure. This condition of slip initiation, referred to as the Coulomb criterion, can then be translated as a limit condition on the magnitude of the vertical and horizontal stress and of the pore pressure, which depends on the inclination of the fault. The formation of a fault follows similar concepts but accounts for an additional shear resistance due to cohesion; also the actual orientation of the created fault corresponds to the inclination for which the condition of slip is first met.

Although the initial in situ stress state and pore pressure are often close to the limit condition required to cause slip on an existing fault, not all perturbations in the stress and pore pressure associated with fluid injection or extraction eventually trigger a seismic event. First, the perturbation must be destabilizing in its nature; that is, it must bring the system closer to critical conditions, irrespective of the magnitude of the perturbation. Indeed some perturbations are stabilizing, meaning that they move the system farther away from critical conditions. The degree of destabilization can be assessed by a certain parameter m that characterizes the nature of the stress and pore pressure perturbation (Figure G.1). Second, if the perturbation is indeed destabilizing, the magnitude of the perturbation has to be large enough to reach critical conditions. Finally, not all slip events are seismic, although most are, as gouge-filled faults could respond in a ductile stable manner.

It is useful to contrast the case of fluid injection in reservoir rocks, where the fluid flows and is stored in the pore network of the rock, from that in crystalline impermeable rocks, where the injected fluid is essentially transmitted and stored in the fracture network. In the permeable case, the pore pressure increases in the rock induce stress variation in the reservoir and in the surrounding rock. In the impermeable case, the stress induced by injection is negligible (except in situations where the fracture network is very dense), but fluid pressure change can be transmitted over a large distance by fractures that offer little resistance to flow. Although our analysis in this appendix refers to a finite-extent reservoir, solution of the infinite case lies within the finite solution. For the purposes of understanding pore

APPENDIX G

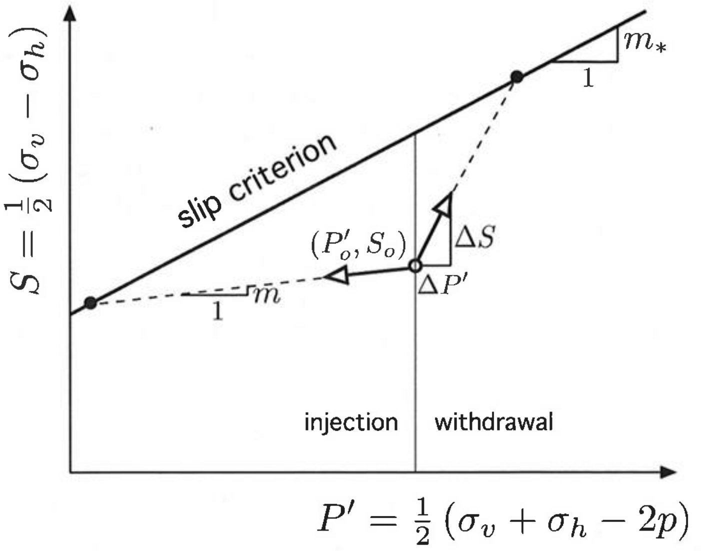

FIGURE G.1 Effective stress change in a reservoir induced by injection or withdrawal of fluid.

pressure perturbation in an infinite reservoir, one simply takes the length of the reservoir to infinity, which causes the reference time scale to go to infinity.

FLUID INJECTION AND EXTRACTION IN A (PERMEABLE) RESERVOIR ROCK

An increase of pore pressure in a permeable rock that is free to deform induces an increase of volume. This physical phenomenon is akin to thermal expansion (i.e., the volume increase experienced by an unconstrained material when subjected to a temperature increase). However, because the deformation of the rock is inhibited by the surrounding material, an increase of pore pressure induces a volume change that is smaller than the unconstrained volume change that would have been for the same pore pressure increase. In addition the compressive stresses in the rock are increased by an amount proportional to the pore pressure increase (see Box 2.3). But for very specific situations, the compressive stress increases in the vertical and in the horizontal directions are unequal, the stress ratio being a function of the shape of the reservoir and the contrast in elastic properties between the reservoir and the surrounding rocks (Rudnicki, 1999, 2002). In particular, the ratio of the induced vertical stress to the induced horizontal stress decreases with the aspect ratio of the reservoir (i.e., the ratio of the reservoir thickness to the lateral extent). For a "thin" reservoir, characterized by a small aspect ratio, the vertical stress change is negligible, and all the stress increase takes place in the horizontal direction, with increases that range between 40 and 80 percent of the pore pressure increase.

The expansion of the reservoir as a whole also alters the stress state in the surrounding rock, in particular inducing a decrease of the horizontal stress above and below a thin reservoir. These stress variations could in principle also trigger normal faulting in these regions; however, the combination of stress and pore pressure change caused by fluid injection is more likely to trigger seismicity in the reservoir rather than outside. The reverse is true for fluid extraction.

FLUID INJECTION IN A FRACTURED IMPERMEABLE ROCK

Unlike fluid injection in permeable rocks, the injection of fluid in fractured impermeable rock is essentially inducing an increase of fluid pressure in the fractures, with negligible concomitant changes in the stress. It is therefore a worst case compared to the permeable rock case, where the increase of pore pressure is in part offset by an increase of the compressive stress, which is a stabilizing factor. (In other words, factor *m* introduced in Figure G.1 is about equal to zero.) Because fractures can be very conductive and offer less storage compared to a permeable rock, the pore pressure perturbations can travel on the order of kilometers from the point of injection.

Coulomb Criterion and Effective Stress

For slip to take place on a fault, a critical condition involving the normal stress σ (the force per unit area normal to the fault), the shear stress τ (the force per unit area parallel to the fault), and the pressure ρ of the fluid on the fault plane, must be met (see Figure G.2 for a representation of σ and τ). This condition is embodied in the Coulomb criterion, $|\tau| = \mu(\sigma - \rho) + c$, which depends on two parameters: the coefficient of friction μ, with values typically in the narrow range from 0.6 to 0.8, and the cohesion c, equal to zero, however, for a frictional fault.

The Coulomb criterion simply expresses that the condition for slip on the fault is met when the magnitude of the "driving" shear stress, $|\tau|$, is equal to the shear resistance $\mu(\sigma - \rho) + c$. The quantity $(\sigma - \rho)$ is known as the effective stress, a concept initially introduced by Terzaghi (1940) in the context of soil failure. It captures the counteracting influence of the fluid pressure ρ on the fault to the stabilizing effect of the compressive stress σ acting across the fault.

As long as the shear resistance is larger than the shear stress magnitude, the fault is stable. However, an increase of the shear stress magnitude or a decrease of the shear strength would cause the fault to slip if the two quantities become equal. For example, an increase of the fluid pressure induced by injection could be responsible for a drop of shear strength large enough to reach the critical conditions.

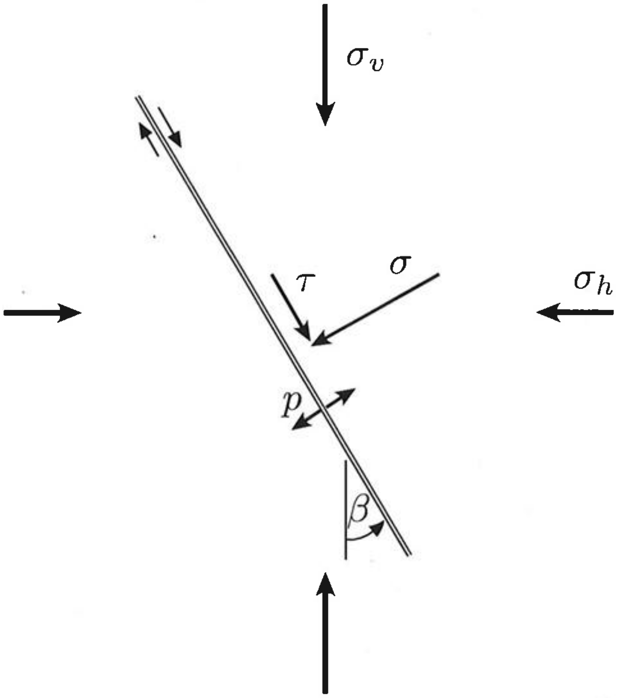

FIGURE G.2 The normal and shear stress, σ and τ, acting across the fault depends on the vertical and horizontal stresses, σ_v and σ_h, and the fault inclination β. The fault is infiltrated by fluid at pressure ρ.

The normal and shear stress on the fault can actually be expressed in terms of the in situ vertical and horizontal stresses, σ_v and σ_h, through a relation that depends on the fault inclination β (Figure G.2). The above Coulomb criterion can then be expressed as a limiting condition in terms of the effective vertical and horizontal stresses $\sigma'_v = \sigma_v - \rho$ and $\sigma'_h = \sigma_h - \rho$ or equivalently in terms of their half-sum and half-difference, *P′* and *S*. Figure G.3 provides a graphical representation of the Coulomb criterion in terms of these two quantities.

The fault is stable if the point representative of the (effective) in situ stress state is below the slip criterion. A perturbation (ΔP′, ΔS), induced by fluid injection or withdrawal, to an existing state (P'_o, S_o) that moves the point ($P'_{o+}\Delta P'$, $S_{o+}\Delta S$) to be on the Coulomb line will cause slip and trigger a seismic event. However, only some perturbations are destabilizing in nature (i.e., they move the representative stress point [P′, S] closer to the critical conditions). For example, the destabilizing perturbation shown in Figure G.3 is characterized by a slope $m = \Delta S/\Delta P'$ smaller than m_o and a "direction" corresponding to both ΔP′ and ΔS being negative. A perturbation characterized by the same slope *m*, but positive variations ΔP′ and ΔS, would be stabilizing.

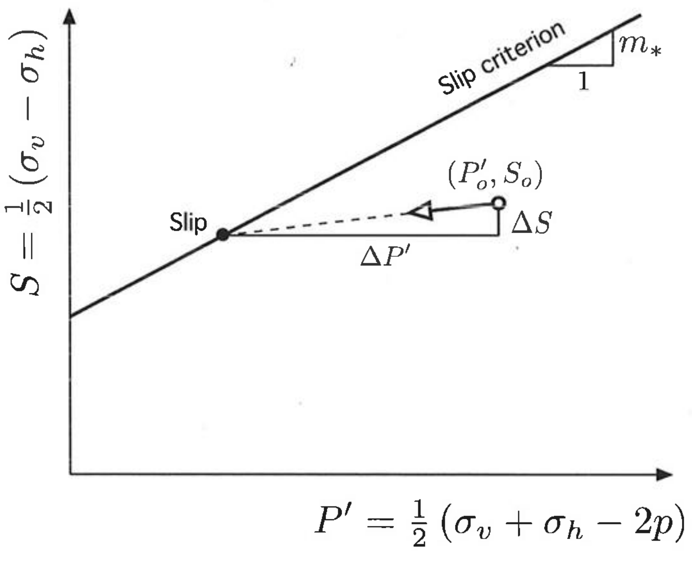

FIGURE G.3 Stress and pore pressure perturbations from an initial stable state leading to critical conditions. The vertical intercept represents the rock cohesive strength and is zero for a preexisting frictional fault. The slope m_o of the slip criterion depends on the friction coefficient μ and on the fault inclination β. The sketch corresponds to the normal conditions when $\sigma'_v > \sigma'_h$.

The existence of a perturbation ΔS reflects the fact that injection or extraction of fluid in deep layers has consequences beyond simply increasing or decreasing the pore fluid pressure. As explained in Chapter 2, the propensity of permeable rocks to expand (contract) as a response to increase (decrease) of pore pressure induces stress change not only in the reservoir but also in the surrounding rocks. Only in the particular case of impermeable rocks, where flow of fluids only takes place in a fracture network, are the perturbations essentially only of a hydraulic nature. For example, injection of fluid in fractured impermeable rock causes mainly an increase of pore pressure Δp leading to $\Delta P' < 0$ and $\Delta S = 0$, which would cause the stress point in Figure G.3 to move horizontally ($m = 0$) to the left.

So far the discussion has been focused on slip on a preexisting fault of known inclination β. The formation of a fault associated with the large-scale shear failure of the rock can be treated within the same framework, with the critical difference that the inclination of the created fault depends only on the friction coefficient μ. It also follows that in the representation of Figure G.3, the slope m_o of the slip criterion (now usually referred to as the Mohr-Coulomb criterion) is exclusively a function of μ. The vertical intercept of the Mohr-Coulomb criterion with the *S* axis then embodies the cohesive shear strength of the rock.