people and structures. For example, if a particular project is observed to generate $\mathbf{M} \geq 2$ earthquakes (i.e., the probability in cell 1A becomes 1 for that project), decisions can be made on pumping characteristics to minimize the probabilities of shaking felt at the surface (cell 2A) and of strong shaking (cell 3A).

Third, the calculated probabilities of shaking felt at the surface (cell 2A), of strong shaking (cell 3A), and of structures and people being affected (cell 4A) can be generalized from those for one project (as depicted in Table 5.2) to forecast the total number of induced seismicity cases that will occur and the number of structures and people affected. If detailed statistical data can be obtained for cells 1B and 2B, this generalization can account for details on forecast locations of projects, volumes and other characteristics of pumping, and proximity to inhabited areas. The estimated numbers of people and structures affected can then become the basis for decisions on whether and how to minimize the impacts of induced seismicity.

Directed research could support development of these steps for the quantification of hazard and risk, with the overall goal of integrating these steps to improve our capability to predict induced events and their consequences. Chapter 6 develops these ideas further by discussing best practices and protocols to avoid or mitigate the impacts of induced seismicity during energy development projects.

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CHAPTER SIX

Steps Toward a "Best Practices" Protocol

THE IMPORTANCE OF CONSIDERING THE ADOPTION OF BEST PRACTICES

This report has shown that induced seismicity may be associated with the development of different energy technologies involving fluid injection and sometimes fluid withdrawal (see, e.g., Chapter 3). Furthermore, despite an increased understanding of the basic causes of induced seismicity (Chapter 2), these kinds of energy development projects will retain a certain level of risk for inducing seismic events that will be felt by members of the public (see Chapter 5). While the events themselves are not likely to be very large or result in any significant damage, they will be of concern to the affected communities and thus require both attention before an energy project involving fluid injection gets under way in areas of known seismic activity (whether tectonic or induced) and management and mitigation of the effects of any felt seismic events that occur during operation.

This chapter outlines specific practices that consider induced seismicity both before and during the actual operation of an energy project and that could be employed in the development of a "best practices" protocol specific to each energy technology. The aim of any eventual best practices protocol would be to diminish the possibility of a felt seismic event from occurring, and to mitigate the effects of an event if one should occur. The committee views the ultimate successes of any such protocol as being fundamentally tied to the strength of the collaborative relationships and dialogue among operators, regulators, the research community, and the public (see also Chapter 4). Indeed, protocols, when properly developed and understood, can serve to protect and benefit the various parties involved both directly and indirectly in energy project development.

The chapter begins with a few examples of induced seismicity "checklists" and protocols in the literature that have been developed for the purpose of management of induced seismicity for specific energy projects. The chapter then discusses some of the key components of these checklists and protocols and develops two induced seismicity protocol "templates," one for enhanced geothermal systems and another for wastewater injection wells. The chapter includes discussion of the incorporation of a "traffic light" system to manage fluid injection and concludes with a discussion of the role and importance of public outreach and engagement prior to and during development of energy projects involving fluid injection. The committee acknowledges that this kind of preemptive management approach embodied in any best practices protocol for induced seismicity can be complicated by the challenges of determining whether any seismicity felt in a region with injection wells is induced or is due to natural, geologic causes (see Chapter 1). However, we suggest that the benefit of the collective dialogue and establishing best practices in the event of a felt seismic event is in itself constructive, with few or no negative consequences.

EXISTING INDUCED SEISMICITY CHECKLISTS AND PROTOCOLS

Induced seismicity does not fall squarely in the sole purview of any single government agency and, in fact, requires input and cooperation among several local, state, and federal entities, as well as operators, researchers, and the public (see Chapter 4). Because of these shared interests and potential responsibilities, the committee suggests that the agency with authority to issue a new injection permit or the authority to revise an existing injection permit is the most appropriate agency to oversee decisions made with respect to induced seismic events, whether before, during, or after an event has occurred. In many cases this responsibility would fall to state agencies that permit injection wells. In areas that are known by experience to be susceptible to induced seismicity, a best practices protocol could be incorporated into the approval process for any proposed (new) injection permit. In areas where induced seismicity occurs, but was not anticipated in a particular area, existing injection permits relevant to that area could be revised to include a best practices protocol.

Two Checklists to Evaluate the Potential for Induced Seismicity and the Probable Cause of Observed Events

Checklists can be convenient tools for government authorities and operators to discuss and assess the potential to trigger seismic events through injection, and to aid in determining if a seismic event is or was induced. Two checklists, one to address each of these two circumstances—the potential for induced seismicity and the determination of the cause of a felt event—were developed nearly two decades ago by Davis and Frohlich (1993) to address each of these circumstances (summarized in the sections that follow). Their work recommends a list of ten "yes" or "no" questions to quantify "whether a proposed injection project is likely to induce a nearby earthquake" and a list of seven similar questions to quantify "whether an ongoing injection project has induced an earthquake."

WILL INJECTION INDUCE EARTHQUAKES: TEN-POINT CHECKLIST

The ten-question checklist evaluates four factors related to possible earthquake hazards: historical background seismicity, local geology, the regional state of stress, and the nature of the proposed injection. Table 6.1, modified from Davis and Frohlich (1993), compares

TABLE 6.1 Criteria to Determine if Injection May Cause Seismicity

	Question	NO APPARENT RISK	CLEAR RISK	Texas City, Texas	Tracy, Quebec	Denver RMA, Colorado
	Background Seismicity					
1a	Are large earthquakes (**M** ≥ 5.5) known in the region (within several hundred km)?	NO	YES	NO	YES	YES
1b	Are earthquakes known near the injection site (within 20 km)	NO	YES	NO	YES	NO?
1c	Is rate of activity near the injection site (within 20 km) high?	NO	YES	NO	NO	NO
	Local Geology					
2a	Are faults mapped within 20 km of the site?	NO	YES	YES	YES	NO?
2b	If so, are these faults known to be active?	NO	YES	NO	NO	NO
2c	Is the site near (within several hundred km of) tectonically active features?	NO	YES	NO?	YES	YES
	State of Stress					
3	Do stress measurements in the region suggest rock is close to failure?	NO	YES	NO	NO?	YES[a]
	Injection Practices					
4a	Are (proposed) injection practices sufficient for failure?	NO	YES	NO?	YES	YES[a]
4b	If injection has been ongoing at the site, is injection correlated with the occurrence of earthquakes?	NO	YES	NO	N.A.	N.A.
4c	Are nearby injection wells associated with earthquakes?	NO	YES	NO	N.A.	N.A.
	TOTAL "YES" ANSWERS	0	10	**1**	**5**	**4**

[a] Assumes stress measurements completed prior to survey.

NOTE: RMA, Rocky Mountain Arsenal.

SOURCE: Davis and Frohlich (1993).

the answers of this ten-point criteria list for three injection wells. The wells listed include an existing injection well located in Texas, a proposed injection project in Quebec, and the injection well located at Rocky Mountain Arsenal in Denver with questions answered "as if injection had not yet taken place."

The authors note, "In actuality, if one were to propose injection at a site near Denver today, the existence of the earthquake activity between 1962 and 1972 would alter the profile, and there would be six or more 'yes' answers" (p. 214). The authors go on to say, "At the Tracy, Quebec site we find five 'yes' answers. . . . We would thus conclude that the situation is more similar to Denver than the Texas Gulf Coast" (p. 214).

Did Injection Induce the Observed Earthquake(s): Seven-Point Checklist

The list of seven questions from Davis and Frohlich (1993) again evaluates four factors related to possible cause: background seismicity, temporal correlation, spatial correlation, and injection practices. In Table 6.2 the seven questions are listed and are specifically phrased so that a "yes" answer would indicate underground injection induced the earthquake(s) and a "no" answer would indicate the earthquake(s) were not caused by injection.

Two injection wells are evaluated in Table 6.2. The well in Denver, Colorado, was the injection well at the Rocky Mountain Arsenal, which was definitely shown to be the cause of induced earthquakes in the mid-1960s. The Painesville, Ohio, well, also known as the Calhio well, which was injecting liquid waste from agricultural manufacturing, was investigated as a cause of earthquakes and revealed ambiguous results; the scientists who examined the data could not make a certain correlation between the injection well and the earthquakes, in part due to historical (natural) seismic activity in the area.[1]

An Example Best Practices Protocol for Induced Seismicity Associated with Enhanced Geothermal Systems

As an example of a protocol used in projects expected to result in induced seismicity, the Department of Energy (DOE) has published a best practices protocol for addressing the potential of induced seismicity associated with the development of enhanced geothermal systems (EGS) (Majer et al., 2012). The steps that a developer might follow in that protocol are summarized in Box 6.1. The DOE states that this protocol is not intended as a proposed substitute to existing local, state, and /or federal regulations but instead is intended to serve as a guideline for the systematic evaluation and management of the anticipated effects of the induced seismicity that are expected to become related to the development of an EGS project.

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[1] For example, see www.dnr.state.oh.us/geosurvey/earthquakes/860131/860131/tabid/8365/Default.aspx.

TABLE 6.2 Seven Questions Forming a Profile of a Seismic Sequence

	Question	Earthquakes Clearly NOT Induced	Earthquakes Clearly Induced	I Denver, Colorado	II Painesville, Ohio
	Background Seismicity				
1	Are these events the first known earthquakes of this character in the region?	NO	YES	YES	NO
	Temporal Correlation				
2	Is there a clear correlation between injection and seismicity?	NO	YES	YES	NO
	Spatial Correlation				
3a	Are epicenters near wells (within 5 km)?	NO	YES	YES	YES?
3b	Do some earthquakes occur at or near injection depths?	NO	YES	YES	YES?
3c	If not, are there known geologic structures that may channel flow to sites of earthquakes?	NO	YES	NO?	NO?
	Injection Practices				
4a	Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?	NO	YES	YES	YES
4b	Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	NO	YES	YES?	NO?
	TOTAL "YES" ANSWERS	0	7	6	3

SOURCE: Davis and Frohlich (1993).

Using this protocol as a foundation, the committee has adapted the protocol's set of seven steps in Table 6.3 to illustrate a set of parallel activities, with steps 2 through 7 undertaken essentially concurrently, as opposed to sequentially, to help manage and mitigate induced seismicity from injection associated with EGS. Viewing a protocol as a set of parallel activities is useful not only for general project management but also for the ability it provides to reassess the protocol through time as circumstances of an energy project change and more data are acquired. This resulting matrix form can be used as a template to develop an appropriate protocol to mitigate the potential to induce seismicity in other

BOX 6.1
The Department of Energy Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems

The elevated downhole fluid pressures used in EGS induce fracturing that can result in a level of induced seismicity that is felt at the surface and that in some cases has caused serious concern among those living nearby (see Chapter 3). To attempt to avoid the repeated occurrence of such results, while encouraging the future use of geothermal resources, a protocol has evolved to serve as a guide for EGS developers within the United States as well as internationally. The most current protocol, developed by the Department of Energy (Majer et al., 2012), "outlines the suggested steps that a developer should follow to address induced seismicity issues, implement an outreach campaign and cooperate with regulatory authorities and local groups." This sequence of seven steps can be summarized as follows:

STEP 1. *Perform Preliminary Screening Evaluation.* Assess the feasibility of the proposed project as to its technical, socioeconomic, and financial risks in order to provide an initial measure of the project's potential acceptability and ultimate success. Review local regulatory conditions, the level of natural seismicity, and the probable impacts of the project on any nearby communities and sensitive facilities.

STEP 2. *Implement an Outreach and Communication Program.* Before operations begin, implement a public relations plan that describes the proposed operations, determine the resulting concerns, address those concerns, and then periodically meet with the locals to explain the upcoming operations and the results of the work done to date.

STEP 3. *Review and Select Criteria for Ground Vibration and Noise.* Identify and evaluate local environmental and regulatory standards for induced vibration and noise. Develop appropriate acceptance criteria for an EGS project.

STEP 4. *Establish Local Seismic Monitoring.* Collect baseline data on the regional seismicity that exists before operations begin. Install and operate a local seismometer array to monitor the project's operations.

STEP 5. *Quantify the Hazard from Natural and Induced Seismic Events.* Estimate the ground shaking hazard from the natural seismicity to provide a baseline to evaluate the additional hazard from the induced seismicity.

STEP 6. *Characterize the Risk of Induced Seismic Events.* Characterize the expected induced ground motion and identify the assets and their vulnerability within the area likely to be influenced by the project.

STEP 7. *Develop a Risk-Based Mitigation Plan.* If the level of seismic impacts becomes unacceptable, direct mitigation measures are needed to further control the seismicity. A "traffic light" system can allow operations to continue as is (GREEN), or require changes in the operations to reduce the seismic impact (AMBER), or require a suspension of operations (RED) to allow time for further analysis. Indirect mitigation may include community support and compensation.

energy technologies. The committee has done this exercise for induced seismicity associated with injection wells used for oil and gas development (Environmental Protection Agency [EPA] Underground Injection Control [UIC] Class II wells) or with carbon storage (EPA UIC Class VI wells) and has developed an example of the primary elements that might be included in a best practices protocol matrix (Table 6.4).

THE USE OF A TRAFFIC LIGHT CONTROL SYSTEM

The protocols described in Box 6.1 and Tables 6.3 and 6.4 refer to a "traffic light" control system for responding to an instance of induced seismicity. Such a system, although rarely employed in energy technology projects with active cases of induced seismicity,[2] allows for low levels of seismicity but adds additional monitoring and mitigation requirements when seismic events are of sufficient intensity to result in a concern for public health and safety. The preferred criterion to be used for such a control system has been the level of ground motion observed at the site of the sensitive receptor, be it a public or private facility. Seismic event magnitude alone is generally insufficient as the only criterion because of the nature of attenuation (absorption or loss of energy) with increasing distance from an event location to a sensitive receptor site. Zoback (2012) provides a summary of a traffic light system for the purpose of managing potential induced seismicity from wastewater disposal.

As an example, the Bureau of Land Management (BLM) recently issued as its "Conditions of Approval"[3] for a proposed EGS project the specific procedures to be followed in the event that induced seismicity is observed to be caused by the proposed stimulation (hydraulic fracturing) operation. The specific procedures included the use of the traffic light control system that allows hydraulic fracturing to proceed as planned (green light) if it does not result in an intensity of ground motion in excess of Mercalli IV ("light" shaking with an acceleration of less than 3.9%g), as recorded by an instrument located at the site of public concern. However, if ground motion accelerations in the range of 3.9%g to 9.2%g are repeatedly recorded within one week, equivalent to Mercalli V ("moderate" shaking), then the operation is required to be scaled back (yellow light) to reduce the potential for the further occurrence of such events. And finally, if the operation results in a recorded acceleration of greater than 9.2%g, resulting in "strong" Mercalli VI or greater shaking, then the active operation is to immediately cease (red light).

The authority for the permitting of Class II injection well location varies by state and is discussed in Chapter 4. Well permits of Class II injection wells in Colorado, for example, are reviewed by the Colorado Geological Survey (COGCC, 2011). During a geologic review,

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[2] To the committee's knowledge, the traffic light system has been applied only at the Berlin geothermal field in El Salvador (Majer et al., 2007) and at Basel, Switzerland.

[3] R.M. Estabrook, BLM, Conditions of Approval for GSN-340-09-06, Work Authorized: Hydroshear, The Geysers, January 31, 2012.

TABLE 6.3 Primary Elements of a Protocol for Addressing Induced Seismicity in EGS Technologies Adapted as a Series of Parallel Activities Extending over the Lifetime of the Operation

Initial Screening to Determine the Feasibility of the EGS Project	Assess the local hazard potential from natural seismicity; the local, state, and federal regulations; the nearness of the project to population centers; the probable magnitude of induced events; and the probable risks of potential damage from both natural and induced events. If the proposed EGS project appears to be feasible based on this initial screening assessment, then the **Essential Activities of the EGS project as listed below** are recommended to proceed in the manner described within each of the five sequential stages of project development as identified herein.				
Category of Essential Activities	PREPARATION STAGE	DRILLING STAGE	STIMULATION STAGE	OPERATIONS STAGE	COMPLETION STAGE
Public and Regulatory Communications	Identify the local people and organizations to be met with. Hold an initial public meeting, explain the planned project, identify their concerns.	Meet with and inform the public, regulators, and media as to the drilling schedule. Upon completion meet and explain the drilling results.	Meet with and inform the public, regulators, and media as to the stimulation schedule and results.	Meet with and inform the public, regulators, and media as to the operations schedule and results.	Meet with and inform the public, regulators, and media as to the project completion.
Criteria for Ground Vibration and Noise	Install ground motion and noise monitoring instrumentations.	Report to the public, regulators, and media the monitoring results.	Report to the public, regulators, and media the monitoring results.	Report to the public, regulators, and media the monitoring results.	Report to the public, regulators, and media the monitoring results.
Seismic Monitoring	Determine areal size and sensitivity needed for local array. Install and operate the seismic recording array and allow timely public access to results.	Continue to monitor the seismicity recorded and publically report the results.	Add and/or reposition array's seismometers as needed to follow and characterize the induced events.	Add and/or reposition array's seismometers as needed to follow and characterize the induced events.	Continue to record and report on the induced seismicity as long as needed to describe the local conditions.

Hazard Assessment	Evaluate the potential additional hazard to be expected from the locally induced seismicity.	Review and reassess the potential for damage based on local observations.	Review and reassess the potential for damage based on local observations.	Review and reassess the potential for damage based on local observations.	Report to the public, regulators, and media on any actual hazards observed.
Risk Assessment	Develop a probabilistic risk analysis to estimate the probability of risk (monetary loss) to be expected.	Revise the Risk Assessment as appropriate, based on any physical damage, nuisance, and/or economic losses attributed to the project operations.			Report to the public, regulators, and media on the actual results experienced.
Direct Mitigation Plans	Develop a plan to control the level and impact of locally induced seismicity.	If needed, implement the control system to cause the drilling, stimulation, or continuing operations to be temporarily reduced or suspended until the level of the locally induced seismicity has been returned to an acceptable level, as determined by the regulatory agencies.			Report to the public, regulators, and media on the actual results experienced.
Indirect Mitigation Plans	Provide local jobs, support local community facilities, and provide compensation if appropriate. Continue indirect mitigation activities as long as needed.				

TABLE 6.4 Summary of the Primary Elements of a Protocol for Addressing Induced Seismicity Associated with Injection Wells Used for Oil and Gas Development (EPA UIC Class II wells) or Associated with Carbon Sequestration (EPA UIC Class VI wells)

	Additional UIC Permitting Requirements	After Drilling and Prior to Injection (A Second Look)	Monitoring Requirements During Injection
Public and Regulatory Communications	Operator should identify local residents and cities and counties that could be affected by induced seismicity and hold public meetings to explain project and identify concerns.	Operator should notify appropriate regulatory agencies and the local public and provide updated information and analysis based on any new information obtained during drilling operations.	Operator should provide periodic updates to appropriate regulatory agencies and the local public on the locations and extent of their injection operations and the locally observed seismic activity.
Hazard Assessment	Evaluate the potential additional hazard to be expected from locally induced seismicity.	Review and reassess the potential for induced seismicity based on any additional information obtained during drilling and completion of the injection well.	Report to the appropriate regulatory agencies and the public on any actual hazards observed during injection activity.
Risk Assessment	Develop a probabilistic risk analysis to estimate the probability of risk to be expected.	Revise the risk assessment as appropriate based on any additional information obtained during the drilling and completion of the injection well.	Revise the risk assessment as appropriate based on additional information obtained during injection activity.
Criteria for Ground Vibration	Determine areal size, sensitivity, and appropriate instrumentation needed for local array.		

Seismic Monitoring	Install and operate the seismic recording array to obtain baseline seismic data and record seismic events due to injection activity.		
Mitigation Plans	Develop a plan to control the level and impact of locally induced seismicity based on the hazard and risk assessment and baseline seismic data.	Revise mitigation plan as appropriate based on any additional information obtained during the drilling and completion of the injection well.	Continuously review and assess mitigation plan to determine effectiveness.

NOTE: The entire protocol would apply to injection wells proposed in areas where induced seismicity has actually occurred. In areas where induced seismicity was not expected but later occurred, the shaded requirements would apply as revisions to the original injection permit.

the historical earthquake data near the well are closely examined, along with any published fault maps in the area. Additional data regarding fault information, such as that available from three-dimensional (3D) seismic images or other geological information from the well operator may be requested if the well appears to be sited in a high-risk area.

MITIGATING THE EFFECTS OF INDUCED SEISMICITY ON PUBLIC AND PRIVATE FACILITIES

The best practices protocols appropriately include an emphasis on establishing a public relations plan to inform the public as well as the appropriate regulatory agencies of the purpose of the proposed or existing project, the intended operations, and the expected impacts on the nearby communities and/or facilities. Public acceptance begins with an understanding of what is expected to transpire and what contingencies exist for dealing with the unexpected. Inherent in any public information and communication plan is the idea that a developer regularly meets with the local public to explain the schedule and activities of each upcoming stage of operations, as well as the results of the operations performed to date. During the committee's information gathering session in The Geysers in Northern California and at the associated workshop in Berkeley, we had an opportunity to discuss the 50-year history of induced seismicity at The Geysers geothermal field and meet with the operators, regulatory authorities, researchers, and the local residents from Anderson Springs and Cobb, nearest to The Geysers operations, and subject to the effects of ground shaking due to induced seismicity (see Appendix B—meeting agenda). The discussions we had with these individuals provided some interesting lessons (Box 6.2) regarding the value and potential success of constructive public engagement, for all parties, when induced seismicity may be or becomes an issue in an energy development project. The committee found several very important points to consider regarding the value of successful public outreach, using this example from The Geysers:

1. **Time**. Public engagement, even if begun early in a project's planning processes, is a process that occurs over a long time and not a goal in itself. As a process, public engagement requires dedicated and frequent communications among industry, the public, government officials, and researchers.
2. **Information and education**. Although the initial burden to supply information and to educate local residents lies with the operator and government authorities, residents, too, have a responsibility to become informed and to be constructive purveyors of data and information back to those responsible for operations to allow constructive dialogue to take place.
3. **Managed expectations through transparency**. Coupled to the sharing of information and education is the idea of managing expectations. Each group involved

BOX 6.2
The Geysers: Toward Mitigating the Effects of Induced Seismicity

About 40 years ago researchers at the U.S. Geological Survey (USGS) and elsewhere began reporting that induced seismicity was associated with the geothermal production and injection operation at The Geysers (e.g., Hamilton and Muffler, 1972). At first, the causes of the seismicity in this area, where natural seismic activity has a long history, were unclear to the seismologists and to the local operators. Following the installation of additional seismometers to increase the accuracy of locating the events, it became evident that the earthquakes were primarily associated with the injection wells associated with The Geysers and, indeed, essential for continued operation of the field to produce electricity (see Chapter 3; Box 3.1). Consequently, when a pipeline project was proposed 15 years ago to deliver wastewater for increased injection at The Geysers to maintain and enhance power generation, the Environmental Impact Report required the establishment of a Seismic Monitoring Advisory Committee (SMAC) to monitor and report on the production and injection, and seismic activities.

The committee includes representatives of the Bureau of Land Management and California state regulatory agencies, county government, the USGS and Lawrence Berkeley National Laboratory, the local communities, and the operators of the geothermal facilities. Real-time results of the seismic monitoring are continuously available to all at the Northern California Seismic website, and the semiannual meetings of this committee provide a forum for all the stakeholders to compare the locations and magnitudes of the reported seismic events to the locations of the reported production and injection activities.

Despite the benefits of establishing the SMAC, the geothermal operators were still viewed by some local residents as not having taken sufficient responsibility for mitigating the effects of the clearly increased numbers of induced seismic events being felt within the local communities (see Box 3.1), and a petition was filed to declare the situation as being a public nuisance. The county government established two subcommittees to deal directly with the residents of the two local communities of Anderson Springs and Cobb. Each subcommittee has representatives of its local community, the local operators, and the local county supervisor. Ground motion recording instruments were installed in each community, and the resulting information is available in near real time at an independently controlled website. This information allows anyone with Internet access to compare the recorded time of an observed ground motion with the reported times of the separately reported local seismic events in order to determine the location of the apparent source that caused the observed ground motion.

The members of each subcommittee have developed a system of receiving, reviewing, and approving damage claims attributed to the local induced seismicity. Over the past 6 years the geothermal operators have reimbursed the homeowners for their costs to have their home damages repaired, at a total expense of less than $100,000 while contributing funds far in excess of this for improvements to the common facilities in the local communities. In addition the county government has continued to contribute to these communities part of the mitigation funds it receives as redistributions of the royalty payments made to the federal government by the local geothermal operators. This system of coordinating the use of the combined resources of both industry and local government has much improved the mitigation of the effects of the locally induced seismicity, and it is now resulting in much improved and mutually satisfactory relationships among the parties.

SOURCES: DOE (2009); J. Gospe, Anderson Springs Community Alliance, 2011, "Man-Made Earthquakes & Anderson Springs," DVD, June 30; see also www.andersonsprings.org/.

in an energy development project has different goals and expectations. Mutual understanding of other groups' goals and expectations is fundamental to developing strong and constructive communication. Transparency regarding these goals and expectations is important to their management.

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CHAPTER SEVEN

Addressing Induced Seismicity: Findings, Conclusions, Research, and Proposed Actions

Induced seismic activity attributed to a range of human activities has been documented since at least the 1920s. However, recent induced seismic events related to energy technology development projects that involve fluid injection or withdrawal in the United States have drawn heightened public attention. Although none of these events resulted in loss of life or significant damage, their effects were felt by local residents. These induced seismic events, though usually small in scale, can be disturbing for the public and raise concern about additional seismic activity and its consequences in areas where energy development is ongoing or planned. The findings, gaps, proposed actions, and research recommendations outlined in this chapter, based upon material presented earlier in the report, address

- the types and causes of induced seismicity;
- issues specific to each energy technology addressed in the study (geothermal energy, conventional and unconventional oil and gas production, injection wells for disposal of wastewater associated with energy development, and carbon capture and storage [CCS]);
- oversight, monitoring, and coordination of underground injection activities to help avoid felt induced seismicity;
- hazards and risk assessment; and
- best practices.

Although credible and viable research into possible induced seismic events has been conducted to date by industry, the academic community, and the federal government, further research is required because of the potential controversies surrounding such events. The Department of Energy, the U.S. Geological Survey, and the National Science Foundation are important organizations both for conducting and for supporting this kind of research and research partnerships with industry and academia. In addition to proposed actions to address induced seismicity, research recommendations are specifically highlighted in Box 7.1; some of these recommendations are specific to individual energy technologies, but most can be conducted with a purpose to understand induced seismicity more broadly.

BOX 7.1
Research Recommendations

Data Collection—Field and Laboratory

1. Collect, categorize, and evaluate data on potential induced seismic events in the field. High-quality seismic data are central to this effort. Research should identify the key types of data to be collected and data collection protocol.
2. Conduct research to establish the means of making in situ stress measurements nondestructively.
3. Conduct additional field research on microseisms in natural fracture systems including field-scale observations of the very small events and their native fractures.
4. Conduct focused research on the effect of temperature variations on stressed jointed rock systems. Although of immediate relevance to geothermal energy projects, the results would benefit understanding of induced seismicity in other energy technologies.
5. Conduct research that might clarify the in situ links among injection rate, pressure, and event size.

Instrumentation

1. Conduct research to address the gaps in current knowledge and availability of instrumentation: Such research would allow the geothermal industry, for example, to develop this domestic renewable source more effectively for electricity generation.

Hazard and Risk Assessment

1. Direct research to develop steps for hazard and risk assessment for single energy development projects (as described in Chapter 5, Table 5.2).

TYPES AND CAUSES OF INDUCED SEISMICITY

Findings

1. The basic mechanisms that can induce seismicity related to energy-related injection and extraction activities are not mysterious and are presently well understood.
2. Only a very small fraction of injection and extraction activities among the hundreds of thousands of energy development wells in the United States have induced seismicity at levels that are noticeable to the public.
3. Current models employed to understand the predictability of the size and location of earthquakes through time in response to net fluid injection or withdrawal

Modeling

1. Identify ways in which simulation models can be scaled appropriately to make the required predictions of the field observations reported.
2. Conduct focused research to advance development of linked geomechanical and earthquake simulation models that could be utilized to better understand potential induced seismicity and relate this to number and size of seismic events.
3. Use currently available and new geomechanical and earthquake simulation models to identify the most critical geological characteristics, fluid injection or withdrawal parameters, and rock and fault properties controlling induced seismicity.
4. Develop simulation capabilities that integrate existing reservoir modeling capabilities with earthquake simulation modeling for hazard and risk assessment. These models can be refined on a probabilistic basis as more data and observations are gathered and analyzed.
5. Continue to develop capabilities with coupled reservoir fluid flow and geomechanical simulation codes to understand the processes underlying the occurrence of seismicity after geothermal wells have been shut in; the results may also contribute to understanding post-shut-in seismicity in relation to other energy technologies.

Research Specific to CCS with Potential to Understand Induced Seismicity Broadly

1. Use some of the many active fields where CO_2 flooding for enhanced oil recovery (EOR) is conducted to understand more about the apparent lack of felt induced seismic events in these fields; because CO_2 is compressible in the gaseous phase are other factors beyond pore pressure important to understand in terms of CCS?
2. Develop models to estimate the potential earthquake magnitude that could be induced by large-scale CCS.
3. Develop detailed physicochemical and fluid mechanical models for injection of supercritical CO_2 into potential storage aquifers.

require calibration from data from field observations. The success of these models is compromised in large part due to the lack of basic data at most locations on the interactions among rock, faults, and fluid as a complex system.

4. Increase of pore pressure above ambient value due to injection of fluids or decrease in pore pressure below ambient value due to extraction of fluids has the potential to produce seismic events. For such activities to cause these events, a certain combination of conditions has to exist simultaneously:
    a. Significant change in net pore pressure in a reservoir
    b. A preexisting, near-critical state of stress along a fracture or fault that is determined by crustal stresses and the fracture or fault orientation
    c. Fault-rock properties supportive of brittle failure

5. Independent capability exists for geomechanical modeling of pore pressure, temperature, and rock stress changes induced by injection and extraction and for modeling of earthquake sequences given knowledge of stress changes, pore pressure changes, and fault characteristics.
6. The range of scales over which significant responses arise in the Earth with respect to induced seismic events is very wide and challenges the ability of models to simulate and eventually predict observations from the field.

Gaps

1. The basic data on fault locations and properties, in situ stresses, pore pressures, and rock properties are insufficient to implement existing models with accuracy on a site-specific basis.
2. Current predictive models cannot properly quantify or estimate the seismic efficiency and mode of failure; geomechanical deformation can be modeled, but a challenge exists to relate this to number and size of seismic events.

Proposed Actions

The actions proposed to advance understanding of the types and causes of induced seismicity involve research recommendations outlined in Box 7.1. These recommendations also have relevance for specific energy technologies and address gaps in understanding induced seismicity.

ENERGY TECHNOLOGIES: HOW THEY WORK

Overarching Findings for All Technologies

1. Injection pressures and net fluid volumes in energy technologies, such as geothermal energy and oil and gas production, are generally controlled to avoid increasing pore pressure in the reservoir above the initial reservoir pore pressure. These technologies thus appear less problematic in terms of inducing felt seismic events than technologies that result in a significant net increase or decrease in fluid volume.
2. The basic data needed to fully evaluate the potential for induced seismicity—including fault locations and properties, in situ stresses, fluid pressures, and rock properties—are very difficult and expensive to obtain.
3. Existing regional seismic arrays may not be capable of precisely locating small induced seismic events to determine causality and better establish the characteristics of induced seismicity.

4. Temporary local seismic arrays can be installed to find faults, determine source mechanisms, decrease error in location of seismic events, and increase resolution of future events.

GAP

Simple geometric considerations to help visualize subsurface problems and identify cases that deserve further attention are in most cases absent. Developing these kinds of simple analyses could, for example, be applied to understand the length scale affected by a single well or by multiple wells relative to depth or proximity to major faults and to the surface.

PROPOSED ACTION

In locales where a causal relationship may exist between subsurface energy activities and seismicity (even for small earthquakes of **M** between 3 and 4), a local seismic array should be installed for seismic monitoring. An appropriate body to determine whether such an array is necessary may be the permitting agency for the well(s) thought to be involved in the seismicity. Installation of such an array may require significant resources (including instrumentation and analysis). Existing groups, such as the U.S. Geological Survey, national laboratories, state geological surveys, universities, and private companies have the expertise necessary to install arrays and conduct the necessary analyses. Full disclosure of the data and results of such monitoring is required.

Geothermal Energy

FINDINGS

1. The induced seismic responses to injection differ in cause and magnitude with each of the three different forms of geothermal resources. At the vapor-dominated Geysers field hundreds of earthquakes of **M** 2 or greater are produced annually with one or two of **M** 4, all apparently caused principally by cooling and contraction of the reservoir rocks. The liquid-dominated field developments generally cause little if any induced seismicity because the water injection typically replaces similar quantities of fluid extracted at similar pressures and temperatures. The high-pressure hydraulic fracturing into generally impermeable rock associated with the stimulation operations at enhanced geothermal systems (EGS) projects can cause hundreds of small microseismic events and an occasional earthquake of up to **M** 3 due mainly to the imposed increased fluid pressures.

2. The mitigation of the effects of induced seismicity is in some instances clearly necessary to maintain or to restore public acceptance of the geothermal power generation activities. The early use of a "best practices" protocol and a "traffic light" control system indicates that such measures can provide an effective means to control operations so that the intensity of the induced seismicity is within acceptable levels. Further information on implementation of a protocol and control system is outlined under the final section in this chapter, Best Practices.

GAPS

1. Suitable coupled reservoir fluid flow and geomechanical simulation codes are not currently available to understand the processes underlying the occurrence of seismicity after geothermal wells have been shut in (ceased operation).
2. Field operators currently do not have ready access to downhole temperature and pressure recording instruments capable of making accurate measurements where reservoir conditions reach 750°F.

PROPOSED ACTIONS

1. Adopt and use a matrix-style "best practices" protocol by developers as outlined in Chapter 6: Such a protocol is appropriate to use in those cases where there is a known probability of inducing seismicity at levels that could pose a concern to the public. In those cases where induced seismicity occurs but was previously unanticipated, the developer should consider adopting the protocol procedures needed to complete the project in a manner more satisfactory to the public.
2. Fully disclose and discuss a "traffic light" system in a public forum prior to the start of operations when such a system is to be adopted or imposed. Such disclosure and discussion will ensure that these safeguards are clearly known and understood by all concerned.

Conventional Oil and Gas Development Including Oil and Gas Withdrawal, Secondary Recovery, and Enhanced Oil Recovery

FINDINGS

1. Generally, withdrawal associated with conventional oil and gas recovery has not caused significant seismic events; however, several major earthquakes have been associated with conventional oil and gas withdrawal.

2. Relative to the large number of waterflood projects for secondary recovery, the small number of documented instances of felt induced seismicity suggests such projects pose relatively small risk for events that would be of concern to the public.
3. The committee has not identified any documented, felt induced seismic events associated with EOR (tertiary recovery). The potential for induced seismicity is low in EOR operations as pore pressure is not significantly increased beyond the original levels in the reservoir because injected fluid volumes tend to be balanced by fluid withdrawals.

Unconventional Oil and Gas: Hydraulic Fracturing for Shale Gas Development

FINDINGS

1. The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events. Thirty-five thousand wells have been hydraulically fractured for shale gas development to date in the United States. To date, hydraulic fracturing for shale gas production was cited as the possible cause of one case of felt seismic events in Oklahoma in 2011, the largest of which was **M** 2.8. The quality of the event locations was not adequate to fully establish a direct causal link to the hydraulic fracture treatment. Hydraulic fracturing for shale gas development has been confirmed as the cause of induced seismic events in one case worldwide—in Blackpool, England (maximum **M** 2.3).
2. One case of induced seismicity (maximum **M** 1.9) was documented in Oklahoma in the late 1970s as being caused by hydraulic fracturing for oil and gas development for conventional oil and gas extraction.

PROPOSED ACTION

When a seismic event occurs that appears to be associated with hydraulic fracturing and is considered to be a concern to the health, safety, and welfare of the public, an assessment is needed to understand the causes of the seismicity (see protocol that follows).

Injection Wells for the Disposal of Water Associated with Energy Extraction

FINDINGS

1. The United States currently has approximately 30,000 Class II wastewater disposal wells; very few felt induced seismic events have been reported as either caused by

or likely related to these wells. Rare cases of wastewater injection have produced seismic events, typically less than **M** 5.0.

2. Injected fluid volume, injection rate, injection pressure, and proximity to existing faults and fractures are factors that determine the probability to create a seismic event. High injection volumes in the absence of corresponding extractions may increase pore pressure and in proximity to existing faults could lead to an induced seismic event.
3. The area of potential influence from injection wells may extend over several square miles, and induced seismicity may continue for months to years after injection ceases.
4. Reducing the injection volumes, rates, and pressures has been successful in decreasing rates of felt seismicity in cases where events have been induced.
5. Evaluating the potential for induced seismicity in the location and design of injection wells is difficult because no cost-effective way to locate unmapped faults and measure in situ stress currently exists.

GAPS

1. Effective and economical tools are not available to accurately predict induced seismic activity prior to injection.
2. No capability exists to predict exactly how reducing volumes, pressures, and rates can lead to reduction in seismicity after it has begun. The models discussed in Chapter 2 are critical to developing the capacity to make such predictions.

PROPOSED ACTIONS

The actions proposed by the committee to address the potential for induced seismicity related to injection wells for disposal of wastewater are similar to those suggested for geothermal energy technologies:

1. The adoption and use of a matrix-style "best practices" protocol as outlined in Chapter 6 in those cases where there is a known probability of inducing seismicity at levels that could pose a concern to the public. In those cases where the need becomes apparent only after disposal has begun, the developer should adopt the protocol procedures needed to complete the project in a manner that protects public safety.
2. When a "traffic light" system is to be adopted or imposed to control operations that could cause unacceptable levels of induced seismicity, full disclosure and discussion of the system at a public forum is necessary prior to the start of opera-

tions. Knowledge and understanding of these safeguards by all concerned are of great importance. Further information is outlined under the final section in this chapter, Best Practices.

Carbon Capture and Storage

FINDINGS

1. The only long-term (~14 years) commercial CO_2 sequestration project in the world at the Sleipner field off the shore of Norway is of a small scale relative to commercial projects proposed in the United States. Extensive seismic monitoring at this offshore site has not indicated any significant induced seismicity.
2. Proposed injection volumes of liquid CO_2 in large-scale sequestration projects (> 1 million metric tonnes per year) are much larger than those associated with the other energy technologies currently being considered. There is no experience with fluid injection at these large scales and little data on seismicity associated with CO_2 pilot projects. If the reservoirs behave in a similar manner to oil and gas fields, these large volumes have the potential to increase the pore pressure over vast areas. Relative to other technologies, such large affected areas may have the potential to increase both the number and the magnitude of seismic events.
3. CO_2 has the potential to react with the host/adjacent rock and cause mineral precipitation or dissolution. The effects of these reactions on potential seismic events are not understood.

GAPS

1. The short- and long-term effects of supercritical CO_2 in influencing rock strength and rock slip strength are not well understood.
2. The potential earthquake magnitudes that can be induced by the injection volumes being proposed for CCS are not known.
3. The complexities of hydrochemical-mechanical effects on CO_2 injection and storage are not thoroughly understood.

PROPOSED ACTIONS

Because of the lack of experience with large-scale fluid injection for CCS, continued research supported by the federal government is needed on the potential for induced seismicity in large-scale CCS projects. Some specific research recommendations are outlined in Box 7.1. As part of a continued research effort, collaboration between federal agencies and foreign operators of CCS sites is important to understand induced seismic events and their effects on CCS operations.

OVERSIGHT, MONITORING, AND COORDINATION OF UNDERGROUND INJECTION ACTIVITIES FOR MITIGATING INDUCED SEISMICITY

Findings

1. Induced seismicity may be produced by a number of different energy technologies and may result from either injection or extraction of fluid. As such, responsibility for oversight of activities that can cause induced seismicity is dispersed among a number of federal and state agencies.
2. Recent, potentially induced seismic events in the United States have been addressed in a variety of manners involving local, state, and federal agencies, and research institutions. These agencies and research institutions may not have resources to address these unexpected events, and more events could stress this ad hoc system.
3. Currently the Environmental Protection Agency (EPA) has primary regulatory responsibility for fluid injection under the Safe Drinking Water Act; however, this act does not explicitly address induced seismicity. EPA appears to be addressing the issue of induced seismicity through a current study in consultation with other federal and state agencies.
4. The U.S. Geological Survey (USGS) has the capability and expertise to address monitoring and research associated with induced seismic events. However, the scope of its mission within the seismic hazard assessment program is focused on large-impact, natural earthquakes. Significant new resources would be required if the USGS mission is expanded to include comprehensive monitoring and research on induced seismicity.

Gap

Mechanisms are lacking for efficient coordination of governmental agency response to seismic events that may have been induced.

Proposed Actions

1. In order to move beyond the current ad hoc approach for responding to induced seismicity, relevant agencies including EPA, USGS, land management agencies, and possibly the Department of Energy, as well as state agencies with authority and relevant expertise (e.g., oil and gas commissions, state geological surveys, state

environmental agencies, etc.) should consider developing coordination mechanisms to address induced seismic events that correlate to established best practices (see recommendation below).

2. Appropriating authorities and agencies with potential responsibility for induced seismicity should consider resource allocations for responding to induced seismic events in the future.

HAZARDS AND RISK ASSESSMENT

Gap

Currently, methods do not exist to implement assessments of hazards upon which risk assessments depend. The types of information and data required to provide a robust hazard assessment would include

- net pore pressures, in situ stresses, and information on faults;
- background seismicity; and
- gross statistics of induced seismicity and fluid injection for the proposed site activity.

Proposed Actions

1. A detailed methodology should be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. The goals in developing the methodology would be to
    - make assessments before operations begin in areas with a known history of felt seismicity and
    - update assessments in response to observed induced seismicity.
2. Data related to fluid injection (well location coordinates, injection depths, injection volumes and pressures, time frames) should be collected by state and federal regulatory authorities in a common format and made accessible to the public (through a coordinating body such as the USGS).
3. In areas of high density of structures and population, regulatory agencies should consider requiring that data to facilitate fault identification for hazard and risk analysis be collected and analyzed before energy operations are initiated.

BEST PRACTICES

Findings

1. The DOE Protocol for EGS, which lists seven sequential steps, provides a reasonable initial model for dealing with induced seismicity that can serve as a template for other energy technologies.
2. Based on this initial model, the committee has proposed two matrix-style protocols as examples to illustrate the manner in which these seven activities can ideally be undertaken concurrently (rather than only sequentially), while also illustrating how these activities should be adjusted as a project progresses from early planning through operations to completion.

Gap

No best practices protocol for addressing induced seismicity is generally in place for each of these technologies, with the exception of the protocol recently developed for EGS. The committee suggests that best practices protocols be adapted and tailored to each technology to allow continued energy technology development. Actions toward developing these protocols are outlined below.

Proposed Actions

1. A matrix-style "best practices" protocol should be developed in coordination with the permitting agency or agencies by experts in the field of each energy technology, including EOR, shale gas production, and CCS.
2. The adoption and use of such protocols by developers are recommended in each case where there is a known or substantial probability of inducing seismicity at levels that could pose a concern to the public. In cases where induced seismicity becomes an issue at some stage in the project, the developer can adopt the protocol procedures needed to continue the project in a manner more satisfactory to the public.
3. Even with the adoption and use of a best practices protocol, induced seismicity of serious concern to public health and safety may occur. The regulatory body affiliated with the permitting of well(s) should include, as part of each project's operation permit, a mechanism (such as a "traffic light" mechanism) for the well operator to be able to control, reduce, or eliminate the potential for felt seismic events.
4. When a traffic light system is to be adopted or imposed to control operations that may cause unacceptable levels of induced seismicity, full disclosure and discussion

of the adopted system at a public forum prior to the start of operations is advised so that these safeguards are clearly known and understood by all concerned. Simultaneous development of public awareness programs by federal or state agencies in cooperation with industry and the research community could aid the public and local officials in understanding and addressing the risks associated with small-magnitude induced seismic events.

Appendixes

APPENDIX A

Committee and Staff Biographies

COMMITTEE BIOGRAPHIES

Murray W. Hitzman (Chair) has been with Colorado School of Mines since 1996 as the Fogarty Professor of Economic Geology. In 2002 he was named Head of the Department of Geology and Geological Engineering. Prior to coming to academia he spent 11 years in the minerals industry. In addition to discovering the carbonate-hosted Lisheen Zn-Pb-Ag deposit in Ireland, he worked on porphyry copper and other intrusive-related deposits, precious metal systems, volcanogenic massive sulfide deposits, sediment-hosted Zn-Pb and Cu deposits, and iron oxide Cu-U-Au-LREE deposits throughout the world. He spent 2½ years in Washington, D.C., working first in the U.S. Senate and later in the White House Office of Science and Technology Policy on environmental and natural resource issues. He has received numerous awards and has published approximately 100 papers. His current interest focuses on deposit- and district-scale studies of metallic ore systems and on social license issues in mining. Dr. Hitzman was a member of the National Research Council's Panel on Technologies for the Mining Industries, and he was a member of Committee on Earth Resources for two 3-year terms prior to becoming chair for a 3-year term in 2004. He received his Ph.D. in geology from Stanford University in 1983.

Donald D. Clarke has worked for the past 6 years as a geological consultant for a variety of private firms and city governments in Southern California, focusing on geological evaluations of oil fields. Part of his current portfolio also includes a CO_2 sequestration project. Prior to establishing his consultancy, he worked for more than 2 decades with the Department of Oil Properties of the City of Long Beach, California, retiring from his position as Division Engineer and Chief Geologist in 2004. During his time with the City of Long Beach, he worked extensively on the giant Wilmington oil field and the California offshore. Mr. Clarke began his career in 1974 as an energy and mineral resources engineer with the California State Lands Commission. His strong interests in community outreach and education have been demonstrated over the years through his teaching geology at Compton Community College, serving on the board of directors for the Petroleum Technology Transfer Council, and serving on and chairing numerous advisory councils and committees of the American Association of Petroleum Geologists (AAPG). A member of AAPG since 1986, he served as Pacific Section AAPG President, was elected to be Chairman of the AAPG House of Delegates, and has received numerous AAPG awards, including the Distinguished Service Award in 2002. He also served on the National Research Council committee that produced the 2002 report *Geoscience Data and Collections: National Resources in Peril*. In the last year he appeared and served as an advisor for the Swiss movie, *A Crude Awakening*; the National Geographic show, *Gallon of Gas* (part of the Man Made Series); and the VBS TV show *LA's Hidden Wells*. This past summer he was interviewed by the Canadian Broadcasting Corporation and Spiegel Television (Germany) about oil development in the Los Angeles area. Mr. Clarke has published or presented more than 50 technical papers on topics that include computer mapping, sequence stratigraphy, horizontal drilling, structural geology, and reservoir evaluation, and he has been recognized by the Institute for the Advancement of Engineering as a fellow. He received his B.S. in geology from California State University, Northridge, with additional graduate study at California State University, Northridge, Los Angeles, and Long Beach.

Emmanuel Detournay is a professor of geomechanics in the Department of Civil Engineering at the University of Minnesota. He also holds a joint appointment with Commonwealth Scientific and Industrial Research Organisation Earth Science and Resource Engineering, where he leads the Drilling Mechanics Group. Prior to his current positions, he was senior research scientist at Schlumberger Cambridge Research in England. His expertise is in petroleum geomechanics with two current areas of focus: mechanics of hydraulic fractures and drilling mechanics. He has authored about 160 papers. He also has been awarded six U.S. patents and has received several scientific awards for his work. Dr. Detournay received his M.S. and Ph.D. in geoengineering from the University of Minnesota.

James H. Dieterich (NAS) is a distinguished professor of geophysics at the University of California, Riverside. His research has led to a new understanding of the Earth's crust. He is an internationally renowned authority in rock mechanics, seismology, and volcanology. His pioneering studies in the theory, measurement, and application of frictional processes in rocks have had major implications for predicting fault instability and earthquake nucleation. His previous work on the rate- and state-dependent representation of fault constitutive properties is now being applied in modeling of seismicity, including aftershocks and triggering of earthquakes, and in inverse models that use earthquake rates to map stress changes in space and time. Dr. Dieterich recently launched a new effort to investigate fault slip and earthquake processes in geometrically complex fault systems, which includes development of large-scale quasidynamic simulations of seismicity in fault systems, and investigation of the physical interactions and stressing conditions that control system-level phenomena. Dr. Dieterich received his Ph.D. in geology and geophysics from Yale University.

David K. Dillon is the principal of David K. Dillon PE, LLC, a petroleum engineering consulting firm located in Centennial, Colorado. He holds a B.S. degree in civil engineering from the University of Colorado at Boulder (1974). He is a licensed professional engineer in Colorado (#19171) and Wyoming (#12530) and has been a member of the Society of Petroleum Engineers for over 35 years. Before starting his career as a consulting engineer, Mr. Dillon worked in the private oil and gas industry for 20 years as a drilling engineer, a production engineer, and a reservoir engineer. He has extensive experience in optimizing production from existing oil and gas fields, secondary recovery operations, and the calculation of oil and gas reserves. Mr. Dillon was also an Engineering Supervisor and the Engineering Manager for the Colorado Oil and Gas Conservation Commission for over 15 years. The Colorado Oil and Gas Conservation Commission is the regulating body for oil and gas drilling and production in the state of Colorado. As the Engineering Manager he was instrumental in the drafting and adoption of new rules by the Commission and the review and approval of underground injection permits for the State of Colorado. Mr. Dillon has offered expert testimony before the oil and gas commissions of several states.

Sidney J. Green (NAE) is research professor at the University of Utah, where he holds a dual appointment in mechanical engineering and civil and environmental engineering. He is also a Schlumberger Senior Advisor and was one of the founders and former President and Chief Executive Officer of TerraTek, a geomechanics engineering firm, which was acquired by Schlumberger in 2006. Mr. Green has worked in the area of geomechanics for nearly 5 decades. He has published numerous papers and reports, holds a number of patents, has given many presentations on geomechanics, and has received a number of rock mechanics and geomechanics recognitions. He has served on government committees and on many university and national laboratory advisory boards, and he has testified at a number of congressional hearings. He has served as member of the board of directors for a number of businesses. He received the Outstanding Engineer award and the Entrepreneur of the Year award from Utah, and the Distinguished Alumni Award (1976) and the Professional Degree recognition (1998) from the former Missouri School of Mines. He received the 1989 Honorary Alumni Award and the 2009 Engineering Achievement Award from the University of Utah. He is a past member of the Greater Salt Lake Chamber of Commerce Board of Governors and was recently elected a Fellow of the American Rock Mechanics Association. He is a member of the U.S. National Academy of Engineering. He most recently served as a member of the NRC Committee on Assessment of the Department of Energy's Methane Hydrate Research and Development Program: Evaluating Methane Hydrate as a Future Energy Resource. Mr. Green has a B.S. from the former Missouri School of Mines and an M.S. from the University of Pittsburgh, both in mechanical engineering. He attended 1 year at Pennsylvania State University graduate school and 2 years at Stanford University, where he received the degree of engineer in engineering mechanics.

Robert M. Habiger worked for ConocoPhillips for over 28 years in various scientific and management capacities in the disciplines of petrophysics and geophysics. While there, he held various positions in research and development and in international exploration, including Manager for Seismic Technology in the Houston corporate offices. He joined Spectraseis as Chief Technology Officer in February 2007, where he is responsible for all technical aspects of the company's research and commercial offerings in passive seismic technology. These programs and products include both hydrocarbon reservoir fluids monitoring from low-frequency passive seismic and microseismic monitoring associated with hydraulic fracturing and fluid injection/removal. Rob is the Director of the Low Frequency Seismic Partnership, an industrial research consortium studying the application of low-frequency passive seismic methods to hydrocarbon fluid mapping. He holds bachelor's, master's, and Ph.D. degrees in physics.

Robin K. McGuire (NAE) is a consulting engineer specializing in earthquake engineering, risk analysis, and decision analysis. His experience includes directing projects to determine earthquake design requirements for new nuclear power plants in the central and eastern United States; making recommendations to the Electric Power Research Institute and the U.S. Nuclear Regulatory Commission on seismic design requirements; consulting for the National Committee on Property Insurance on earthquake matters and making recommendations to the California Department of Insurance; serving as lead consultant on probabilistic performance assessment of the Yucca Mountain site as a possible high-level waste repository; and consulting on numerous U.S. and overseas studies of seismic and environmental risk for utilities, insurance groups, and commercial clients. Dr. McGuire was president of the Seismological Society of America (SSA) in 1991-1992, authored the book *Seismic Hazard and Risk Analysis* in 2004, and was the Joyner Lecturer in 2009 for the Earthquake Engineering Research Institute and the SSA. Dr. McGuire received his S.B. in civil engineering from the Massachusetts Institute of Technology, his M.S. in structural engineering from the University of California, Berkeley, and his Ph.D. in structural engineering from the Massachusetts Institute of Technology.

James K. Mitchell (NAS/NAE) is currently University Distinguished Professor Emeritus at Virginia Polytechnic Institute and State University (Virginia Tech) and Consulting Geotechnical Engineer. Prior to joining Virginia Tech in 1994, he served on the faculty at the University of California, Berkeley, since 1958, holding the Edward G. Cahill and John R. Cahill Chair in the Department of Civil and Environmental Engineering there at the time of his retirement in 1993. Concurrent to his tenure at UC Berkeley, he was Chairman of Civil Engineering from 1979 to 1984. His primary research activities have focused on experimental and analytical studies of soil behavior related to geotechnical problems, admixture stabilization of soils, soil improvement and ground reinforcement, physicochemical phenomena in soils, environmental geotechnics, time-dependent behavior of soils, in situ measurement of soil properties, and mitigation of ground failure risk during earthquakes. He has authored more than 375 publications, including the graduate-level text and geotechnical reference *Fundamentals of Soil Behavior*. A licensed civil engineer and geotechnical engineer in California and professional engineer in Virginia, Dr. Mitchell has served as chairman or officer for numerous national and international organizations. He has chaired the NRC Geotechnical Board and three NRC study committees, and served as a member of several other NRC study committees. He has received numerous awards, including the Norman Medal and the Outstanding Projects and Leaders Award from the American Society of Civil Engineers, and the NASA Medal for Exceptional Scientific Achievement. He was elected to the National Academy of Engineering in 1976 and to the National Academy of Sciences in 1998. Dr. Mitchell received a bachelor of civil engineering from Rensselaer Polytechnic Institute, and M.S. and doctor of science degrees in civil engineering from the Massachusetts Institute of Technology.

Julie E. Shemeta is the president and founder of MEQGeo Inc., a microseismic consulting and services company based in Denver, Colorado. She has worked on microseismic projects in North America, Australia, and India, including hydraulic fracture monitoring in tight gas, shale gas and oil, steam-assisted gravity drainage, and coalbed methane projects. Her background includes deep-water oil and gas exploration in the Gulf of Mexico, working in the geothermal industry for developments in Indonesia and the Philippines, and working for a microseismic vendor providing data processing and consulting on hydraulic fracture monitoring. Ms. Shemeta has been actively involved with the development of software for both processing and visualization of microseismic throughout her 20-year career. She has served on numerous meeting committees for the Society of Exploration Geophysicists, the Society of Petroleum Engineers, and the AAPG. She co-chaired the DGS/RMAG (Denver Geophysical Society and Rocky Mountain Association of Geologists) 3-D Seismic Symposium from 2009 to 2011 and is still active on the committee. She served as the Denver Geophysical Society Treasurer in 2008-2009. She obtained her B.S. in geology at the University of Washington and her M.S. in geophysics with a specialty in earthquake seismology at the University of Utah.

John L. (Bill) Smith is presently a geothermal consultant having recently retired as a senior geologist at the Northern California Power Agency (NCPA). He has 46 years of diversified geologic, geophysical, and geochemical experience in the geothermal and oil and gas industry, including numerous geothermal exploration and development projects in the western United States and Japan. For the past 25 years he has worked at The Geysers, first designing, permitting, and evaluating steam production and water injection wells to initially supply a 220 MW power project, and then for more than the past decade monitoring the induced seismicity that occurs both within the NCPA area of operations and throughout the entire Geysers field. Prior to joining The Geysers, Dr. Smith worked for 10 years as an oil and gas exploration geologist and geophysicist (seismologist) for Standard Oil of California (Chevron), then for 11 years as Vice President of Exploration for Republic Geothermal, which included geothermal exploration and development projects throughout California, Nevada, Utah, and Japan. Dr. Smith received his A.B. in geology from Middlebury College and his M.A. and Ph.D. in geological sciences from Indiana University.

STAFF BIOGRAPHIES

Elizabeth A. Eide is director of the Board on Earth Sciences and Resources at the NRC. Prior to joining the NRC as a staff officer in 2005, she served as a researcher, team leader, and laboratory manager for 12 years at the Geological Survey of Norway in Trondheim. In Norway her research included basic and applied projects related to isotope geochronology, mineralogy and petrology, and crustal processes. Her publications include more than 40 journal articles and book chapters, and 10 Geological Survey reports. She has overseen 10 NRC studies. She completed a Ph.D. in geology at Stanford University and received a B.A. in geology from Franklin and Marshall College.

Courtney Gibbs is a program associate with the NRC Board on Earth Sciences and Resources. She received her degree in graphic design from the Pittsburgh Technical Institute in 2000 and began working for the National Academies in 2004. Prior to her work with the board, Ms. Gibbs supported the Nuclear and Radiation Studies Board and the former Board on Radiation Effects Research.

Jason R. Ortego is a research associate with the Board on Earth Sciences and Resources at the National Academies. He received a B.A. in English from Louisiana State University in 2004 and an M.A. in international affairs from George Washington University in 2008. He began working for the National Academies in 2008 with the Board on Energy and Environmental Systems, and in 2009 he joined the Board on Earth Sciences and Resources.

Nicholas D. Rogers is a financial and research associate with the National Research Council Board on Earth Sciences and Resources. He received a B.A. in history, with a focus on the history of science and early American history, from Western Connecticut State University in 2004. He began working for the National Academies in 2006 and has primarily supported the board on a broad array of Earth resources, mapping, and geographical sciences issues.

APPENDIX B

Meeting Agendas

MEETING 1

Washington, DC, April 26-27, 2011

DAY ONE

08:00-09:00	CLOSED SESSION (Committee & NRC Staff only)
09:00-09:15	***Doors open; registration***
09:15-15:00	**OPEN SESSION—PUBLIC WELCOME TO ATTEND**
09:15-09:30	Welcome and introductions *Murray Hitzman, Chair*
09:30-15:00	**Presentations**
09:30-10:30	**Department of Energy** **George Guthrie**, Office of Fossil Energy/National Energy Technology Laboratory **JoAnn Milliken and Jay Nathwani**, Geothermal Technologies Program
10:30-11:00	**Allyson Anderson**, Professional staff, U.S. Senate Energy and Natural Resources Committee
11:00-11:15	Break
11:15-12:00	**Ernie Majer**, Senior Advisor to the ESD Director and Energy Program Leader, Lawrence Berkeley National Laboratory
12:00-13:00	*Lunch*
13:00-13:45	**Cliff Frohlich**, Professor, University of Texas at Austin

13:45-14:30 **Domenico Giardini,** Director, Swiss Seismological Service

14:30-15:00 General discussion *Murray Hitzman, Chair*

End of open session

15:00-17:00 CLOSED SESSION (Committee & NRC Staff only)

End of session

DAY TWO

08:00-13:30 CLOSED SESSION (Committee & NRC Staff only)

End of meeting

MEETING 2

The Geysers, CA, and Lawrence Berkeley National Laboratory, CA, July 13-15, 2011

DAY ONE

Committee members tour Geysers, led by representatives from NCPA and Calpine

DAY TWO

09:15-16:45 OPEN SESSION—PUBLIC WELCOME TO ATTEND

09:15-09:25 Welcome and introduction to study *Murray Hitzman, Chair*

09:25-12:30 Panel discussions

09:25-10:15 **Panel 1—Vapor-dominated geothermal resource development**
Melinda Wright, Calpine Corporation
Craig Hartline, Calpine Corporation
Bill Smith, Northern California Power Agency

10:15-10:45	**Panel 2—Liquid-dominated geothermal resource development** Charlene Wardlow, Ormat
10:45-11:00	*Break*
11:00-12:30	**Panel 3—EGS resource development** Mark Walters, Calpine Corporation Julio Garcia, Calpine Corporation Susan Petty, Chief Technology Officer, AltaRock Energy Inc. Ernst Huenges, Head of Reservoir Technologies, GFZ Potsdam Jay Nathwani, Department of Energy Geothermal Technologies Program
12:20-13:30	Lunch presentation— Ernie Majer, Lawrence Berkeley National Laboratory, on the topic of the Department of Energy Induced Seismicity Protocol
13:30-16:30	**Presentations**
13:30-14:00	**Federal land management** Linda Christian, Bureau of Land Management Oregon/Washington
14:00-15:00	**Community contributions** Mark Dellinger, Jeffrey Gospe, Hamilton Hess, Meriel Medrano, Cheryl Engels
15:00-15:15	*Break*
15:15-16:30	**Research** David Oppenheimer, USGS Jean Savy, Lawrence Berkeley National Laboratory
16:30-17:00	General discussion *Murray Hitzman, Chair*

End of open session

DAY THREE

08:00-12:00	**CLOSED SESSION (Committee & NRC Staff only)**

End of meeting

MEETING 3

Irvine, CA, August 18, 2011

08:30-14:15 OPEN SESSION—PUBLIC WELCOME TO ATTEND

08:30-08:40 Welcome and introduction to study *Murray Hitzman, Chair*

08:45-15:00 Presentations (presentations + time for discussion)

08:45-10:00 **Ola Eiken and Philip Ringrose,** *Statoil AS*
CO_2 sequestration and monitoring activities offshore Norway
Overview of CO_2 Monitoring Activities Offshore Norway (Sleipner, Snøhvit)—*Ola Eiken*
Future plans for microseismic and surface monitoring onshore and offshore—*Philip Ringrose*

10:00-10:15 *Break*

10:15-11:15 **James Rutledge,** *Los Alamos National Laboratory*

11:15-12:30 **Mark Zoback,** *Stanford University*
The potential for triggered seismicity associated with CO_2 sequestration and shale gas development

12:30-13:15 *Lunch*

13:15-14:15 **Michael Bruno,** *Terralog Technologies*

End of open session

MEETING 4

Dallas, TX, September 14-15, 2011

DAY ONE

07:30-08:15 CLOSED SESSION—COMMITTEE AND NRC STAFF ONLY

08:30-17:30 OPEN SESSION—PUBLIC WELCOME TO ATTEND

08:30-08:45 Welcome and Introductory Remarks *Murray Hitzman, Committee Chair*

Morning session moderated by Don Clarke and Jim Mitchell, Committee members

08:45-09:20 **Norm Warpinski**, Pinnacle—A Halliburton Service
Induced seismicity in shale stimulations

09:20-09:55 **Leo Eisner**, Czech Academy of Sciences and Seismik, Ltd.
Case examples of induced seismic events near shale gas operations

09:55-10:35 **Scott Ausbrooks**, Arkansas Geological Survey
Steve Horton, University of Memphis
Earthquakes in central Arkansas triggered by fluid injection at Class 2 UIC wells

10:35-10:50 Break

10:50-11:20 **John Jeffers**, Southwestern Energy
Observations and perspectives on induced seismicity and microseismicity associated with shale gas development

11:20-11:55 **Serge Shapiro**, Free University of Berlin
Quantitative understanding of induced microseismicity for reservoir characterization and development

11:55-12:30 **Doug Johnson**, Texas Railroad Commission
Regulatory response to induced seismicity in Texas

12:30-13:15 Lunch

Afternoon session moderated by David Dillon and Robin McGuire, Committee members

13:15-13:45 **Lisa Block**, Bureau of Reclamation
Deep injection of brine and monitored induced seismicity in Paradox Valley

13:45-14:15 **Philip Dellinger**, Environmental Protection Agency
Summary of EPA's current work with induced seismicity issues

14:15-14:50 **Shawn Maxwell**, Schlumberger
Overview of hydraulic fracture mapping

14:50-15:00 Break

15:00-15:40 **Rob Finley**, Illinois State Geological Survey
Midwest Geological Sequestration Consortium—Overview of approaches to induced seismicity

15:40-16:15 **Steve Melzer**, Melzer Consulting
Tertiary production and CO_2 enhanced oil recovery including conceptual risk of injection, reservoir surveillance, and sequestration monitoring

16:15-16:45 Wrap-up discussion *Moderated by Murray Hitzman*

End of Open Session

DAY TWO

07:45-09:45 CLOSED SESSION, COMMITTEE AND STAFF ONLY

10:00-13:00 OPEN SESSION—PUBLIC WELCOME TO ATTEND

10:00-10:10 Introductory Remarks *Murray Hitzman, Committee chair*

10:10-12:00 Panel discussion *Moderated by Julie Shemeta, Committee member*

Werner Heigl, Apache Corporation
Jamie Rich, Devon Energy

12:00-13:00 Lunch

End of open session

13:00-17:00 CLOSED SESSION, COMMITTEE AND NRC STAFF ONLY

DAY THREE

07:30-12:00 CLOSED SESSION, COMMITTEE AND STAFF ONLY

End of meeting

MEETING 5

Washington, DC, November 10-11, 2011

DAY ONE

08:00-09:30 CLOSED SESSION—COMMITTEE AND STAFF ONLY

09:30-10:45 OPEN SESSION—PUBLIC WELCOME

09:30-09:40	Welcome and Introductory Remarks	*Murray Hitzman, Committee Chair*
09:40-10:00	**Allyson Anderson**, Professional staff, U.S. Senate Energy and Natural Resources Committee	
10:00-10:15	**Jay Braitsch**, Department of Energy—Fossil Energy	
10:15-10:30	**Jay Nathwani,** Department of Energy—Geothermal Technologies Program	
10:30-10:45	General discussion	
10:45-11:00	*Break*	

End Open Session