WORKSHOP ON INDUCED SEISMICITY DUE TO FLUID INJECTION/PRODUCTION FROM ENERGY-RELATED APPLICATIONS

FINAL REPORT AND RECOMMENDATIONS

Workshop held at Stanford University, Bechtel Conference Center
February 4, 2010

LAWRENCE BERKELEY NATIONAL LABORATORY

Contributors

This paper is the work product of the following participants of the workshop:

Participants	Institution	Observers	Institution
Hiroshi Asanuma	Tohoku University		
Horst Rueter	HarbourDom U.	Avi Gopstein	DOE
Brian Stump	Southern Methodist University	Arlene Anderson	DOE
Paul Segall	Stanford	Alison Labonte	DOE
Mark Zoback	Stanford	Hildigunnur (Hidda) Thorsteinsson	DOE
Jim Nelson	WIAI	Allan Jelacic	NWT
Cliff Frohlich	University of Texas	George Guthrie	DOE/NETL
Jim Rutledge	LANL	Ben Phillips	NSF
Roland Gritto	AIT	Maryann Villavert (scribe)	LBNL
Roy Baria	MIL-TECH UK	Doug Blankenship (scribe)	SNL
Steve Hickman	USGS	Mack Kennedy (scribe)	LBNL
Ernie Majer	LBNL	Jim Berryman	LBNL
Art McGarr	USGS	Pat Dobson (scribe)	LBNL
Bill Ellsworth	USGS	Colin Williams	USGS
Dave Lockner	USGS	Don Jucket	AAPG
David Oppenheimer	USGS	Hamilton Hess	FOCM
Peter Henning	Conoco-Phillips	Gillian Foulger	AltaRock
Anca Rosca	Chevron	Sue Petty	AltaRock
Brian Hornby	BP	Joe Iovenitti	AltaRock
Herb Wang	University of Wisconsin	Melinda Wright	Calpine
Nick Beeler	USGS	Ali Kahn	State CA
Ahmad Ghassemi	Texas A&M		
Mark Walters	Calpine		
Ann Robertson-Tait	Geothermix		
Peter Dracos	Ormat		
Mike Fehler	MIT		
Ahmed Abou-Sayed	ATI		
Jon Ake	Nuclear Regulatory Commission		
Oleg Vorobiev	LLNL		
Bruce Julian	USGS/Foulger Consulting		

Table of Contents

Executive Summary

Geothermal energy, carbon sequestration, and enhanced oil and gas recovery have a clear role in U.S. energy policy, both in securing cost-effective energy and reducing atmospheric CO_2 accumulations. Recent publicity surrounding induced seismicity at several geothermal and oil and gas sites points out the need to develop improved standards and practices to avoid issues that may unduly inhibit or stop the above technologies from fulfilling their full potential. It is critical that policy makers and the general community be assured that EGS, CO_2 sequestration, enhanced oil/gas recovery, and other technologies relying on fluid injections, will be designed to reduce induced seismicity to an acceptable level, and be developed in a safe and cost-effective manner.

Induced seismicity is not new—it has occurred as part of many different energy and industrial applications (reservoir impoundment, mining, oil recovery, construction, waste disposal, conventional geothermal). With proper study/research and engineering controls, induced seismicity should eventually allow safe and cost- effective implementation of any of these technologies. In addition, microseismicity is now being used as a remote sensing tool for understanding and measuring the success of injecting fluid into the subsurface in a variety of applications, including the enhancement of formation permeability through fracture creation/reactivation, tracking fluid migration and storage, and physics associated with stress redistribution.

This potential problem was envisaged in 2004 following observed seismicity at several EGS sites, a study was implemented by DOE to produce a white paper and a protocol (Majer et al 2008) to help potential investors. Recently, however, there have been a significant number of adverse comments by the press regarding induced seismicity which could adversely affect the development of the energy sector in the USA. Therefore, in order to identify critical technology and research that was necessary not only to make fluid injections safe, but an economic asset, DOE organized a series of workshops. The first workshop was held on February 4, 2010, at Stanford University. A second workshop will be held in mid-2010 to address the critical elements of a "best practices/protocol" that industry could use as a guide to move forward with safe implementation of fluid injections/production for energy-related applications, i.e., a risk mitigation plan, and specific recommendations for industry to follow.

The objectives of the first workshop were to identify critical technology and research needs/approaches to advance the understanding of induced seismicity associated with energy related fluid injection/production, such that:

1. The risk associated with induced seismicity can be reduced to a level that is acceptable to the public, policy makers, and regulators.

2. Seismicity can be utilized/controlled to monitor, manage, and optimize the desired fluid behavior in a cost effective fashion.

There were two primary goals during the workshop:

1. Identify the critical roadblocks preventing the necessary understanding of human-induced seismicity. These roadblocks could be technology related (better imaging of faults and fractures, more accurate fluid tracking, improved stress measurements, etc.), research related (fundamental understanding of rock physical properties and geochemical fluid/rock interactions, development of improved constitutive relations, improved understanding of rock failure, improved data processing and modeling, etc.), or a combination of both.

2. After laying out the roadblocks the second goal was to identify technology development and research needs that could be implemented in the near future to address the above objectives.

The main results of the workshop were as follows:

- It was recognized that addressing issues associated with induced seismicity is critical in allowing the implementation of injection technology associated with current and future geothermal, carbon sequestration, and certain injection-dependent oil and gas projects.

- The relatively short-term injections to induce hydrofractures for oil and gas recovery pose little or no induced-seismicity threat to the public. The main concern for the oil and gas industry is injecting produced or waste water in large volumes for long periods into the subsurface in zones/depths that may be prone to induced seismicity.

- For EGS and CO_2 sequestration, although attention is now being focused on current near term injections, issues associated with long-term injections (10’s of years) may be just as or more, important to understand.

- The general consensus was that there are research and technology barriers that must be overcome to safely and effectively advance the subject technologies; however, these barriers can be addressed by advancing some key technologies using focused field, modeling and lab studies, and performing research in certain key areas.

- There is a wealth of data that is yet to be analyzed, especially from EGS sites. These projects are set in different geology and stress regimes. One could use these data sets to develop a model which replicated the seismicity observed in these fields to test current models and advance our understanding of induced seismicity. This may show areas of further field experiments which are necessary to further develop or improve existing models to observe and predict reservoir stress deformation, accumulation of stresses in specific areas, and ultimately the release of locked strain energy for the understanding induced seismicity processes. Parallel with this, high quality instrumentation, data acquisition and processing should continue and implemented in some sites for testing. This will also help us to design stimulations by which we can control the build up stress and thus control large induced events.

- There was a general consensus that high-quality data are still lacking for certain studies that could be obtained by deploying state-of-the-art instrumentation at current and future injection sites. There was considerable support among academic researchers at the workshop for dedicated field sites, preferably not under commercial control or constraints. But there was general agreement that much could also be learned from current commercial sites, especially if experimental sites could be located at commercial operations where a large amount of characterization data was already available.

- Identified were key instrumentation needs for high-temperature applications as well as drilling technology needs (mainly for emplacing instrumentation in intermediate depth wells in order to obtain wide-bandwidth, large-dynamic-range data in a cost-effective fashion) that if developed, would not only address near-term needs, but be valuable for long-term commercial applications.

- A critical recommendation was that an updated engineering guide/protocol that identifies a means of accurately assessing risk and mitigating unacceptable seismicity should be developed and provided to industry as soon as possible. This would allow current and proposed projects to

- It was again pointed out how important it is to reach out to the community and bring the public, policy makers and regulators into the process of addressing induced seismicity from the very beginning.

Workshop Objectives

Identify critical technology and research needs/approaches to advance the understanding of induced seismicity associated with energy-related fluid injection/production, such that:

1. The risk associated with induced seismicity can be reduced to a level acceptable to the public, policy makers, and regulators.

2. Seismicity can be confidently utilized/controlled to monitor, manage, and optimize the desired fluid behavior in the subsurface.

Workshop Goals

There were two primary goals:

1. Identify the critical roadblocks preventing the necessary understanding of human-induced seismicity. These roadblocks could be technology related (better imaging of faults and fractures, more accurate fluid tracking, improved stress measurements, instrumentation etc.) research related (fundamental understanding of rock physical properties and geochemical fluid/rock interactions, development of improved constitutive relations, improved understanding of rock failure, improved data processing and modeling, etc.), or a combination of both research and technology.

2. Once the roadblocks were laid out, the next step was to identify the technology development and research activities that could be implemented in the near future to address the first objective, with the overall objective of obtaining the necessary understanding to manage and control human-related seismicity associated with energy-related fluid injection/production.

Workshop Structure

The workshop was started by describing the current background and status of issues surrounding induced seismicity, followed by a discussion of past cases and current issues with induced seismicity. (See attached; workshop description, list of participants, agenda, and notes Appendix I.) The goal, as described above, was to identify the main roadblocks that must be overcome to reach our objectives. In addition to identifying the roadblocks, the participants were asked to present ideas on the technology and research central to solving the stated roadblock. Questions considered included:

1. What basic or applied field, lab, or theoretical/modeling research should be conducted in addressing the roadblock?
2. What new technology (or current technology not being used, but could be) should be implemented to better understand, manage, and control induced seismicity?
3. How can technology needed for induced seismicity be leveraged across geothermal, carbon sequestration, and oil and gas applications?

Critical Questions and Issues Identified

As stated above, one of the critical issues surrounding induced seismicity is how to accurately, and on a timely basis, assess the risk associated with induced seismicity for any project. Current and potential operators of projects utilizing fluid injection and/or extraction need to know the practices that will satisfy the safety concerns of the public and regulators, such that the project can move forward. For example, in some instances, a particular project may be proposed for areas in which seismicity is common, such as in the Western U.S. In these areas, there already may be assessments of seismic risk/maximum ground motion from "natural seismicity." The question then becomes, how does one assess the increased risk due to fluid injection beyond the current risk (if any)? In other cases, the risk from natural seismicity may not be well known, or very low, because historical seismicity has also been low in the proposed project area. In such instances, how does one assess the increased risk of unwanted seismicity due to fluid injections? It was also noted that induced seismicity has been observed in areas of low historical seismicity; therefore, relying solely on past history could obviously lead to inaccurate estimates of risk. In either case (endpoints), the risk to a particular project may not be *hazardous* seismicity (seismicity harmful to structures and people), but *unacceptable* seismicity—seismicity that is not acceptable to the local community or regulators, owing to a variety of factors such as property values, quality of life, and long-term impacts.

It was also pointed out that it is important to define what is meant by "risk". In a probabilistic sense risk was described as the product of three factors: (1) the annual frequency of an event, (2) the probability of that particular event exceeding a desired threshold (causing failure or some other undesired outcome), and (3) the consequence of the event exceeding that threshold (measured in dollars, or some metric of interest—public outcry, rejection of technology, etc.). A seismic event may happen quite often, and be large, but if it occurs in a remote area where there is no consequence, the risk would be calculated as low. On the other hand, in areas of high population, infrequent, small events may cause community concern and opposition; thus, the consequence is regarded as high and the risk may be high.

During the workshop, it was pointed out that any measure of acceptable seismicity should be based on acceptable ground motion, not on actual magnitude. For example, if larger events are far away from any population or structures of concern, they may be less of a risk than smaller events close to structures or population centers. It was also pointed out that the uncertainty associated with estimating any of the three risk components must be as small as possible; otherwise, it would be very difficult to assess the risk accurately. Moreover, several other participants pointed out the critical need for awareness of the public reaction to seismicity in assessing the risk associated with induced seismicity. Thus, the community must be educated with respect to all of the issues and be comfortable that the first two factors in the risk analysis (frequency and probability of an event exceeding the acceptable threshold) are based upon solid science, accurate data, proper procedures, and correct assumptions. Once public trust is lost, it is difficult to reacquire it.

The basic questions asked in determining the risk associated with induced seismicity were:

1. What is the largest ground motion from an earthquake that can be expected (how does one estimate the future seismicity when there is little data (or none or historical seismicity)on past seismicity?
2. Will small events lead to bigger events in the same area?
3. Can smaller events trigger larger events on nearby faults?
4. How many events can one expect, and in what sizes?

5. What is the volume threshold over which the injection/production activities would cause unacceptable induced seismicity?
6. How does one control induced seismicity?
7. What controls are (will be) in place to mitigate induced seismicity?
8. If seismicity occurs, how long will it persist, and can it be controlled before it becomes unacceptable?
9. What plans/compensation should be in place if unacceptable seismicity occurs (from small to large)
10. How the in-situ stress affects the generation of induced seismicity.

The main issue then becomes, what studies, technology, research, measurements, etc., must be done to answer the above questions? Is the technology and understanding of earthquake mechanics in place to achieve that objective, or is new research and technology necessary?

In reality, we will never completely answer all of these questions (if we could, we could probably accurately predict earthquakes), but there are actions that can be done to reduce the uncertainty associated with answering these questions, and actions that can be undertaken to mitigate the risk associated with induced seismicity.

The above questions led to several key requirements that were identified to address the above questions:

1. Almost all were in agreement that obtaining as much information as possible (prior to commercial injection) about the subsurface stress field was critical in assessing the potential for induced seismicity. It was also acknowledged that it is quite difficult to map the subsurface stress field in detail. Lack of direct measurements from boreholes, unmapped faults, and the natural complexity in rock properties all contribute to the overall uncertainty in estimating the stress field. For example, the stress field is important if one addresses such questions as: For a critically stressed fault, will a pore-pressure increase at a shallow depth trigger slip at the depth of the naturally occurring events, which may be much deeper? What are the effects of temperature change/thermal stresses/subsidence, etc., due to injection?

2. The past history of seismicity is also important for estimating stress distribution and rate of natural stress release in potential areas of induced seismicity, as well as for estimating the directions of regional stress. For example, if the proposed project is in a seismically active region with a long history of "natural" seismicity (several magnitude 2's and 3's per year, with an occasional 4 or larger), then one may want to very carefully consider this project area for injection, because it may be more prone to induced seismicity than aseismic areas. This is not always true—it was pointed out that in several case studies, significant induced seismicity occurred where there was little prior seismicity (Paradox Valley in Colorado was given as an example.) Again, the existing stress field and its relation to levels of critical failure are important in assessing the forces available that could cause seismicity.

3. In general, ongoing seismicity indicates stress buildup and release that may be more easily triggered by fluid injection. This does not automatically rule out a site (it may be far from local communities), but care should be taken. Also, the depth of the current seismicity is important. Large earthquakes (over magnitude 5) need larger stress accumulations and in general start deeper than smaller events; if the background seismicity is occurring at all depths, then it may be an indication of the stress distribution. It is also important to examine any seismicity from any past injections in the subject region. If there have been other injections (for any other reasons), and there has been very little or no seismicity, this may indicate an acceptable area in which to inject.

The relation of the stress field (orientation and magnitude of principal stress directions) to existing faults was also deemed important. For example, do faults have the dimensions that could cause unacceptable seismicity? Are all the potential slip planes that may cause unacceptable seismicity identified? Where are the potential slip planes relative to the injection points? For example, here is sometimes a correlation between the accumulated seismic energy release and volume injected in EGS systems. Sometimes larger induced seismic events seem to occur after the shut-in or during maintenance periods in hydrothermal fields. The exact mechanism is not understood but it could be due to relation of stress with pressure gradient reversal in a reservoir. There is some evidence in the EGS reservoirs that larger events are more prominent on the boundary of existing reservoir.

4. The mechanisms of failure were also discussed. For fluid injection, what is the relative contribution of fluid pressure effects (rates, volumes, duration, etc.), temperature (stress alteration), and chemical alteration of rock properties? What are the factors that control the range that pore pressure will affect seismicity. It was noted that in some cases, seismicity could be controlled by reducing injection rates, changing/alternating injection points, or doing periodic injections rather than continuous injections. Several key questions mentioned were: What controls the size and rate of events (especially the larger events that sometimes occur after injection stops)? (This led to a discussion on how to determine the "tipping point" for induced seismicity.) How does one determine the threshold of injection that causes unacceptable seismicity? What controls the decay of seismicity after injection stops or larger events occur? How does one determine the radius of influence (how close to a critically stressed fault can one be?) If "natural seismicity" is known to occur much deeper than the planned depths of injection, can one safely inject? What are the similarities and differences between natural and induced earthquakes? What are the relationships among foreshocks, aftershocks, b-values, etc.?

5. In terms of utilizing seismicity for managing reservoir performance, the questions discussed were: What are the relevant and important physics and chemistry, and what key parameters do we need to determine for modeling processes at the appropriate scales (scaling)? What is the degree of coupling among the parameters? How can we correctly interpret geophysically based diagnostic signals (microseismic, tilt, deformation, fracture mapping, fluid mapping, etc.) to help control the injection of fluid needed to stimulate the reservoir? Can we use this knowledge to manage induced seismicity? What controls long-term reservoir performance? Can we establish methods to sustain it using the information from seismicity? What are the "basic" properties of a site required for design, and can we measure them? What technology is needed to measure required parameters?

6. Lastly, how does one formally approach risk assessment. Can Probabilistic Seismic Hazard Analysis (PSHA) be used for induced seismicity cases to estimate the occurrence rates and level of seismicity, as well as estimate the largest events? Most applications of PSHA are for "natural" occurrences of seismicity, in areas where there has been a history of seismicity, fairly well-known fault lengths and mechanisms, and constant stress patterns over a time of interest. For example, if one had tried to apply PSHA to The Geysers, California, field before it was developed, the PSHA estimate would probably have been far from reality. In potential induced-seismicity areas, background seismicity, stress properties, fault lengths, etc., may not be known until events begin to occur as injection proceeds. In fact, there was a discussion regarding the potential for injections to redistribute stress concentrations and accelerate the occurrence of events in some areas and inhibit seismicity in others. On the other hand, it was pointed out that there should be an effort to be responsible to the community and employ some method to estimate the maximum event, based on the best available data. This could possibly be accomplished by comparing the potential injection site to other similar sites; historical seismicity in the area (if any) could be used to place bounds on the larger events. What types of data, analyses, and models are needed to conduct an adequate induced-seismicity risk study? How much baseline data are needed, and at what level of detail?

How will the potential impact of both short-term (i.e., fracture stimulation) and long-term (i.e., sustained injection) be evaluated using limited (temporal, spatial) field data?

As pointed out above, risk assessment needs to be addressed as soon as possible: proposed projects must be able to accurately estimate the induced-seismicity risk to determine if it is below a tolerable level before investing large sums of money and developing a particular site. The risk and estimates of seismicity will be site dependent, based on properties of a particular site under specific conditions. For example, there will be a need to determine the probability of failure/damage of structures/property in order to comply with local building stock, age, type of building codes in use, etc. In addition, zones of low seismic potential may pose greater risk simply because the existing building stock may have been designed to a low seismic code level. Another issue may be ground motion in the Central and Eastern United States (CEUS)—this may be especially problematic due to the high ground-motion levels in the CEUS compared to the Western U.S. Finally, although induced seismicity has been noted in numerous locations in the eastern U.S., seismic monitoring is less detailed than in the Western U.S., and consequently low-magnitude historical data may not be as available. Again, as workshop participants commented, unless the physics and mechanics of the problem are known, it is difficult to derive accurate prior estimates of induced seismicity and thus provide realistic estimates of overall risk.

Recommended Actions and a Path Forward

The recommendations and path forward can be broken down into two main areas

1. What is needed in terms of research/ technology to provide a scientific and technical base for accurately assessing the risk of induced seismicity, in addition to being able to not only mitigate/control the seismicity, but to utilize the seismicity to optimize reservoir performance?

2. In setting the risk level, how does one specify or at least estimate the acceptable level of (ground motion) seismicity for any particular project? It is recognized in civil engineering and mining industry that induced shockwaves from such activities is quantified in terms to manmade structural damage criteria (peak velocity and frequency) which is well established and accepted by public and relevant authorities. This may be a way forward for establishing and acceptance criteria for induced seismic events. It was clear that a successful path forward must balance the operators' economic interests with any impacted community, while also taking into account the overall benefits that the subject technology is providing to the greater community.

The workshop mainly addressed the first question, but it is clear that the second question must be addressed in the short term also.

Research and Technology Needs

1. Field Data for Improved Characterization

A. Seismic Data

In many case histories that were presented, the ability to assess and understand the induced seismicity was limited by not having enough (or proper) data to characterize the seismic source properties, (i.e., we need more and improved seismic data). For example, many case histories that had long-term data did not have comprehensive coverage in frequency content, and/or bandwidth, or enough coverage for focal mechanism determination (mining, fluid disposal, geothermal, oil and gas, reservoir impoundments) and therefore lacked sufficient data coverage for characterization/analysis studies being done, or that could be done today. Although there are many different data sets from a variety of different sites that have been monitored for induced seismicity, there is a lack of consistency in the quality and coverage available in some of the more recent data sets. Needed are earthquake data sets that have wide bandwidth (from a few hertz to hundreds of hertz) with a dynamic range of at least magnitude -1.0 to magnitude 5.0, full azimuthal coverage, and baseline monitoring as well as detailed monitoring before, during, and well after the injections. Borehole installations employing broadband, wide-dynamic-range, multicomponent data are essential in a research mode. It was noted, however, in more recent monitoring (last 10 to 15 years), there does exist data sets from several geothermal sites with modern instrumentation that could be more fully utilized than they are now. The Geysers, California, field and Cooper Basin, Australia, were several examples of active sites that were mentioned. Combined with comprehensive reservoir engineering and geologic data, the data from these sites could play a valuable role in understanding induced seismicity. It is important to note that lack of adequate seismic data not only hinders accurate risk analysis, but also limits understanding of reservoir dynamics for obtaining cost-effective and optimal energy production and/or fluid sequestration.

B. Historical Seismic Data

As mentioned above, some injection sites have more comprehensive historical data sets than others, depending on the location relative to existing seismic monitoring networks and the original intention of those networks. Seismic networks are usually installed to monitor seismicity for understanding hazards from natural seismicity, rather than for induced seismicity. As noted above, however, low seismicity does not necessarily mean no induced seismicity will occur. Therefore, local low-level seismicity may not be known before one selects a potential site. Lack of such data may lead to a misdiagnosis of potential low-level seismicity, stress patterns, and potential for unacceptable (although not hazardous) seimicity.

C. Stress Data

Stress data are critical in understanding and assessing the risk of inducing unacceptable seismicity. Without knowing the direction and magnitude of the stress components, we cannot easily calculate how fluid injection will affect the stress field. Seismicity data may provide general directions, but more knowledge about the *in situ* stress is needed to understand how existing fault/fracture planes may react to changing fluid pressures, temperatures, or other factors. Such factors may readjust the *in situ* stress to exceed the stress at which induced seismicity occurs (and we also need to know how to control the stress changes). Additionally, as one injects in to the formation, the existing stress regime is deformed and redistributed to accommodate the volume of fluid initially and increased aperture following shear displacement. This redistribution is unlikely to be spherical and it is possible that some area will be able to accommodate more strain energy than others causing a high stress build up in specific regions and these may be eventually released as a shockwave.

D. Geologic Data

The geologic conditions such as fault/fracture dimensions, density, and directions need to be known in order to estimate/model the maximum possible magnitude and expected distribution of the seismicity in time as well as in space. This information, along with the stress data, will play an important role in designing the injection location(s) as well as the rate and duration. Rock lithology and mineralology will also be important for accurately modeling the processes controlling seismicity.

E. Reservoir Engineering Data.

Fluids play a central role in seismicity, either through pressure, temperature, or chemical effects, or some combination of the three. Accurate data for pressure, rate, temperature, volumes, and fluid compositions are critical to understanding the interrelation of stress, fluids, and the matrix material. This would feed into not only geomechanical and reservoir engineering models, but also geochemical models. A Shear displacement mechanism is normally associated with the enhancement of permeability in an EGS reservoir and there are theoretical calculation techniques available to estimate the failure but additional laboratory experiments could be useful enhance the understanding of these processes in in-situ or pressurized environment.

F. Other Geophysical/Geochemical Data

Independent data to understand deformation and fluid properties will be needed to validate models, as well as to understand reservoir properties. In many cases, one assumes that the seismicity cloud indicates fluid locations, but other factors—such as pressure diffusion—may be playing a large role. We already know that only pressure has to change, that there doesn't need to be a significant quantity of fluid to alter the effective stress state. The more interesting question is, can thermal effects be dominant? Or can poroelastic stress changes, which can occur even in areas with no change in pore-pressure? Data such as tilt, GPR, precision gravity and INSAR measurements may provide valuable information on overall deformation. In addition, active seismic measurements (VSP and surface reflection) could provide valuable information on fracture locations, hidden faults, and lithology—to feed into models. Finally, electrical methods (EM, IP, resistivity) could map fluid locations and be an independent check on fluid locations.

2. Field Instrumentation

To meet the above characterization requirements, there needs to be two avenues of action, (1) data collection with modern techniques and equipment, and (2) the development of new instrumentation and tools to collect the necessary data.

A. For high frequency seismic acquisition areas (see below for tilt and deformation measurements), we need low-cost methods to collect wide-bandwidth, large-dynamic-range, and comprehensive low-noise data sets (which implies low-cost borehole installations). Modern 24-bit digitizers can be deployed on the surface with commercial tools in dense arrays that can provide large data sets. However, large-element arrays of three component sensors (greater than 25 elements) can become cost prohibitive to smaller projects for long-term monitoring (years). In addition, surface sensors lack the ability to sense high-frequency smaller events that are diagnostic of important reservoir dynamics at the small scale, and may be indicative of potential induced seismicity at the large scale. With the recent development of new and better MEMS (define) and fiber optic sensors (low cost as well) that have much smaller and wider bandwidth than current sensors, one can begin to think about cost-effective deployment of sensor arrays in shallow (a few hundred feet) to medium-depth (few thousand feet) boreholes. Critical, however, is the technology to drill and complete microholes (a few inches in diameter), using a rapid and low-cost method, in which not only seismic sensors can be placed, but other geophysical sensors. This technology is being developed for oil and gas applications, and could be accelerated with interest from geothermal and carbon sequestration applications. This technology need not be high temperature if, for permanent installation, we stay above the high-temperature zone in geothermal applications).

B. An additional category of needs is tools for measuring rock and fluid properties in boreholes. There already exists many commercial companies that will perform a variety of measurements developed for the oil and gas industry, but geothermal and carbon sequestration will need specialized tools. The needs identified were the following:

1. High-temperature (250°C) packers that could be used in open holes.
2. Continued development and commercialization of high temp imaging tools: multilevel seismic characterization, dipole sonic (full waveform)
3. More robust tools for damaged/rough holes and muds (all applications)
4. High-temp., low-flow flow meters (no need for any high temp. if we stay above the high temp. zone)
5. Instrumentation for reliable (accurate zero times and monitoring) of calibration shots in boreholes (all applications) (need HT for Geothermal)
6. A reliable microhole tiltmeter or strain gauge—development for EGS applications (high T) would be particularly challenging. Far-field measurements of strain changes are needed as warning systems and to provide input for models.
7. Development of improved deformation monitoring techniques for boreholes.

3. Rock Physics/Fault Mechanics Research

To some degree, the research studies identified were linked to field and characterization needs. Up to this point, the understanding of induced seismicity is based on empirical studies and observations from actual field sites. It was felt that before we undertake a large rock-physics program or earthquake source mechanism studies, more work is needed to understand existing data, and to analyze new data sets. Using these data sets, one should address questions such as:

A. *Determination of the Difference between Current PSHA for "Natural" Seismicity and Induced Seismicity.* For natural seismicity, the current practice is to use known fault models, deformation models, EQ rate models, and probability models. The main question is: Can you move the current models used for natural seismicity to model to the small scale of reservoirs, i.e., in the current practices, replace the deformation models with a valid stress model. To do this, we will need accurate fault and stress models to determine the EQ rate and probability models (related to perturbations). Key questions to address are:
   a. Does the knowledge of reservoir and surrounding rock mechanics properties (rock strength, fault strength, permeability, porosity, poroelasticity) tell us anything about susceptibility to induced seismicity?
   b. Does induced microseismicity reflect changing rock mechanical properties in an interpretable way?
   c. Does reservoir stimulation increase fault susceptibility to seismic slip?
   d. Does rock failure (from hyrofrac/hydroshear) have any bearing on induced seismic hazard, or is the entire hazard in reactivated events?
   e. Does plastic deformation or shearing of microfractures in shales and mudstones affect their ability to serves as an impermeable seal to fliuids stored in underlying formations?

B. *Candidate Fault Mechanics Research Needs*. Again, many of the questions posed were based on current experience and unknowns related to current projects. By performing research in conjunction with field measurements and characterization studies, many of the questions below could be addressed.
   a. What limits the magnitude of induced earthquakes (size of pressurized zone, length of fault, *in situ* stress properties, etc.)?
   b. We need better knowledge of relation between stress change (particularly effective normal stress) and seismicity rate.
   c. We need to examine the time dependence or stressing-rate dependence in stress-seismicity rate change, we need to include other mechanisms beyond the theory of effective stress, i.e., thermal effects.

d. We need to know slip-dilatancy (slip-permeability) relations better for fault zones.
e. We need to understand about hydrothermal processes (fault healing, permeability reduction) in the induced seismicity problem.
f. We need to know more about fault zone poroelasticity.
g. We need to know more about chemical processes
h. Do induced earthquakes follow the same attenuation relations as tectonic earthquakes in the same province?

C. *Laboratory Studies* **(**note: in geothermal cases, high temperature measurements are also needed). Data from lab studies were identified as being important in providing information for failure models. Needs were identified to provide data acquisition at high temperatures and in the presence of fluids, in addition to fluid interactions. Key questions and needs that should be addressed are:

a. Evolution of fracture permeability and fault strength at *in situ* conditions.
b. Measurement of permeability evolution using rotary shear testing.
c. Effect of large shear displacement on failure criteria.
d. Measurements of gouge production and the development of fines and its effect on permeability.
e. Mechanical properties testing to understand relationship between rock properties and fracturing/shearing results.
f. Measurements to determine the effects of chemical processes in modifying fracture permeability and fault strength over time scales equivalent to a geothermal reservoir.
g. Measurements of geophysical (seismic, electrical) properties to determine the hierarchy of field conditions.

D. *Modeling, Processing and Analysis Needs*. Integrated modeling of stress, pressure, temperature (thermomechanical), and chemical effects on failure mechanisms are needed for both static and dynamic modeling of failure criteria. Any new methodology should be validated at both the lab and field scale.

High priority items are:

1. Advanced methods for modeling dynamic failure and fracture response in 3-D. These should be fluid coupled codes.
2. Analytical methods and results from validating computer codes
3. Moment tensor inversion methods for anisotropic material.
4. Stress analyses for extrapolation beyond boreholes.
5. Improved 3-D tomographic methods for spatial and temporal variations in fluid pressure/fracture density/anisotropy
6. Combined inversions for seismic with fluid sensitive methods (EM resistivity, electrical).
7. Integration of InSAR, tiltmeter, and precision gravity data into deformation models.
8. Location methods. Methods are not lacking; however, knowledgeable personnel must be using software.

4. Integrated Field Measurements and Studies

As was discussed, induced seismicity issues could be a barrier to full-scale implementation for a variety alternative energy technologies, as well as CO_2 reduction methods. Thus, it is important to address induced seismicity with the appropriate resources and scope. This led to the problem of defining the proper scale at which the technical community should be addressing the problem—are we thinking too small? As a consequence, there was considerable discussion regarding the need for developing a dedicated field test facility. Although there are large amounts of seismicity data from past and present geothermal sites that could and should be analyzed and utilized to address many issues, there are no dedicated experimental field sites that have the flexibility to iterate among experimental approaches that commercial operators would/could carry out. At such a site, one could perform experiments that would allow driving the system to failure, or carrying out experiments that would be difficult or not allowed at commercial sites. In addition, one could try different manipulative experiments while collecting a variety of data without commercial constraints. Iterative experiments at different scales could also be done to test different models and theories. For example, one could address scaling issues using data from the lab scale, through the well scale, all the way up to the full reservoir scale. Finding an experimental field site as discussed above would entail locating one with similar geologic conditions to a proposed project. For example, the anticipated rock mechanics at an experimental hot dry rock (HDR) site would vary substantially from an experimental hydrothermally enhanced geothermal site. Therefore, the concept that iterative experiments at an experimental HDR site would yield results applicable to an enhanced hydrothermal could be presumptive. In the same manner, the geology of an experimental field site for carbon sequestration or enhanced oil and gas recovery would necessarily, and substantially, vary from an experimental HDR site. In short, there may be no one-size-fits-all experimental site to study induced seismicity.

In addition, many current industry sites have proprietary data that may not be released—this is especially true in oil and gas environments, which are also candidates for CO_2 sequestration. The test facility would also not only address the hazard and risk issues associated with induced seismicity, but many reservoir-engineering aspects of using induced seismicity for optimizing reservoir performance. Ideally, one of the large benefits of an experimental field site would be determining which methods should be employed on a routine basis for commercial application. Some important questions that could be addressed are:

1. Is it possible to mitigate induced seismicity and optimize production at the same time?
2. Does the reservoir reach equilibrium (seismicity energy release remains constant)?
3. What are the minimum parameters necessary to estimate the seismicity hazard?
4. In terms of larger seismic events, do they have a pattern with respect to the general seismicity, do they increase in rate and size?
5. Can Probabilistic Seismic Hazard Analysis (PSHA) be used for induced seismicity to estimate the largest events? (Try it and see how it works out?)
6. Can experiments be performed that will shed light on key mechanisms causing seismicity?

Facilities at such a site should allow detailed monitoring of not only seismicity in 3-D, utilizing both surface and borehole measurements in detail, but a variety of other critical reservoir properties, such as:

1. Stress distribution and evolution
2. Fracture/fault distribution
3. Fluid states and distribution
4. Deformation from the reservoir level to the surface
5. Fluid loss zones
6. Rock properties (lab testing)
7. Correlation to lab tests with geophysics

Examples of experiments that could be carried out at a dedicated field site are:

1. Variation of injection rates at different pressures, volumes, fluid temperatures, etc., while monitoring seismicity, stress, subsurface pressures, etc.
2. Experiments for developing measurement techniques for critical reservoir parameters (stress, fracture properties, fluid locations, and content)
3. Long-term experiments to intentionally create large events (define) that would not adversely impact nearby communities.
4. Experiments to control seismicity and test various hypotheses on earthquake mechanisms
5. Thermal stressing effects.
6. Validation of geophysical measurements

Specific qualifications for such a field site (including issues brought up) would be as follows:

1. An environmental NEPA study for the experimental field site would allow permitting in a relatively short time period.
2. Any field site should be representative of eventual sites of application. As mentioned above, no one particular site would fit all future applications; therefore, care must be taken to choose a site(s) that is (are) not too general, but would have many attributes of any future sites of application. A possibility is to piggyback on existing industry sites in an area where one could experiment without affecting commercial applications or significantly impact potentially sensitive communities.
3. Scale was an important issue: sites should be large enough to cover multiple ranges of geology, stress, fluid, pressure, etc., but not so large as to be too expensive to develop and maintain.
4. Sites should be well-characterized for stress, fluid, geology (lithology, structure, mineralogy, etc.), with geochemical properties in 3-D.
5. Sites should have a well-known history and not be disturbed to the point of lacking proper background data.
6. A participant commented that the DOE's Regional CO_2 Sequestration Partnerships are now entering their Phase III projects, wherein larger-scale injection into saline aquifers (up to 1M tons per year) will be taking place. Some of these projects could provide excellent opportunities to study induced seismicity in field settings that have not been complicated by a history of fluid extraction and injection operations, as one finds in O&G and EGS projects.
7. The caveat with the CO_2 projects is the lack of data to start with, but the characterization that will be required for assessing risk and designing CO_2 projects should also benefit and include the evaluation and study of induced seismicity.
8. Studying induced seismicity under CO_2 projects would also be attractive in developing and testing downhole instrumentation outside the challenge of high-temperature environments.

In any case, there was considerable interest is pursuing some sort of test facility, either in conjunction with industry or as a dedicated test facility. One possibly that was also discussed to provide an incentive for cost share is to turn the facility over to industry when finished.

Summary

- It was recognized that addressing issues associated with induced seismicity is critical in allowing the implementation of injection technology associated with current and future geothermal, carbon sequestration, and certain injection-dependent oil and gas projects.

- The relatively short-term injections to induce hydrofractures for oil and gas recovery pose little or no induced-seismicity threat to the public. The main concern for the oil and gas industry is injecting produced or waste water in large volumes for long periods into the subsurface in zones/depths that may be prone to induced seismicity.

- For EGS and CO_2 sequestration, although attention is now being focused on current near term injections, issues associated with long-term injections (10's of years) may be just as or more, important to understand.

- The general consensus was that there are research and technology barriers that must be overcome to safely and effectively advance the subject technologies; however, these barriers can be addressed by advancing some key technologies using focused field, modeling and lab studies, and performing research in certain key areas.

- There is a wealth of data that is yet to be analyzed, especially from EGS sites. These projects are set in different geology and stress regimes. One could use these data sets to develop a model which replicated the seismicity observed in these fields to test current models and advance our understanding of induced seismicity. This may show areas of further field experiments which are necessary to further develop or improve existing models to observe and predict reservoir stress deformation, accumulation of stresses in specific areas, and ultimately the release of locked strain energy for the understanding induced seismicity processes. Parallel with this, high quality instrumentation, data acquisition and processing should continue and implemented in some sites for testing. This will also help us to design stimulations by which we can control the build up stress and thus control large induced events.

- There was a general consensus that high-quality data are still lacking for certain studies that could be obtained by deploying state-of-the-art instrumentation at current and future injection sites. There was considerable support among academic researchers at the workshop for dedicated field sites, preferably not under commercial control or constraints. But there was general agreement that much could also be learned from current commercial sites, especially if experimental sites could be located at commercial operations where a large amount of characterization data was already available.

- Identified were key instrumentation needs for high-temperature applications as well as drilling technology needs (mainly for emplacing instrumentation in intermediate depth wells in order to obtain wide-bandwidth, large-dynamic-range data in a cost-effective fashion) that if developed, would not only address near-term needs, but be valuable for long-term commercial applications.

- A critical recommendation was that an updated engineering guide/protocol that identifies a means of accurately assessing risk and mitigating unacceptable seismicity should be developed and provided to industry as soon as possible. This would allow current and proposed projects to advance with confidence, i.e., if followed by industry, such a guide/protocol would assure the public and regulators that these projects could proceed safely.

- It was again pointed out how important it is to reach out to the community and bring the public, policy makers and regulators into the process of addressing induced seismicity from the very beginning.

Reference

Majer, E., Baria, R. and Stark, M. Protocol for induced seismicity associated with enhanced geothermal systems.(2009) Report produced in Task D Annex I (2008), International Energy Agency-Geothermal Implementing Agreement (incorporating comments by: C. Bromley, W. Cumming, A. Jelacic and L. Rybach). Available at: http://www.iea-gia.org/publications.asp.)

APPENDIX

ATTACHMENT 1: Invitation, agenda, and attendees

Workshop on Induced Seismicity due to Fluid Injection/Production from Energy Related Applications

Place: **Stanford University. Bechtel Conference Center**
Time: **Feb 4, 2010, 8AM - 6PM**

Objectives

Identify critical technology and research needs/approaches to advance the understanding of induced seismicity associated with deep well injection and production, such that:

1. The risk associated with induced seismicity can be reduced to a level that is acceptable to the public, policy makers and regulators, and
2. The seismicity can be utilized/controlled to monitor, manage and optimize the desired fluid behavior in the subsurface.

Rationale and Background

Geothermal energy, carbon sequestration and enhanced oil and gas recovery have a clear role in U.S. energy policy and in reducing atmospheric CO2 accumulations. Recent publicity surrounding induced seismicity at several geothermal and oil and gas sites, however, points out the need to develop more rigorous standards and practices to avoid any potential problems with induced seismicity. It is critical that the policy makers and the general community be assured that EGS, CO2 sequestration, enhanced gas recovery, and other technologies relying on fluid injections will be designed to avoid any unacceptable seismicity and be developed in a safe and cost effective manner. Induced seismicity is not new, it has occurred in many different energy and industrial applications (reservoir impoundment, mining, construction, waste disposal, conventional geothermal). However, with proper study and engineering controls, induced seismicity issues have never stopped the eventual safe implementation of any of these technologies. In addition, microseismicity is now being used as a tool for understanding and measuring the success of injecting fluid into the subsurface in a variety of applications, including the enhancement of formation permeability through fracture creation/reactivation and in tracking fluid migration and storage. Proper research and technology development and implementation will significantly aid in the success of these critical technologies.

Workshop Goals

There are two primary goals

1. Identify critical roadblocks that are preventing the necessary understanding of human-related seismicity. These road blocks could be technology related (better imaging of faults and fractures, more accurate fluid tracking, improved stress measurements, etc.) research related (fundamental understanding of rock physical properties and geochemical fluid/rock interactions, development of

improved constitutive relations, improved understanding of rock failure, improved data processing and modeling etc,) or a combination of both research and technology.

2. Once the roadblocks have been laid out, identify the technology development and research activities that can be implemented in the short term (one to two years) and intermediate (five years) to address the first goal, with the overall objective of obtaining the necessary understanding to manage and control human-related seismicity associated with deep well injection. (this is the hard part)

Workshop Structure and Expectations from Participants

Enclosed you will find some background material that was developed during and after the workshops that were held in 2005 and 2006 related to induced seismicity associated with Enhanced Geothermal Systems (EGS). Also attached are some updated documents and recent reports from specific cases of induced seismicity. Please read these materials before the workshop starts.

Each participant was selected due to their expertise and knowledge pertaining to induced seismicity and deep well injection in energy applications. Everyone is expected to share their knowledge and contribute to the overall goals of the workshop. If you are not one of the observers and you feel that you cannot contribute, please do not come, we will understand.

In essence, the morning will be devoted to identifying the technical and scientific roadblocks and unresolved issues, and the afternoon will be devoted to coming up with a practical strategy for getting around or solving these roadblock: i.e., what is it that we need to know and how do we obtain that knowledge?

In addition to help identifying the roadblocks, you should come with ideas on needed technology and research that is central to solving the stated objectives. You are not expected (OR WANTED) to come and present a long power point presentation on a particular project; we do not have time for that. However, you are expected to come prepared to give a short presentations (5 min or so) that will stimulate ideas and discussion to achieve our overall goals of the workshop. <u>Remember this is a workshop not a conference!!</u> Questions we would like you to consider include: What basic or applied field, lab or modeling research should be conducted to address the roadblock? What new technology (or current technology that is not being used, but could be) should be implemented to better manage and control induced seismicity? Think broadly!

Find attached an agenda and a participant list; this is a draft agenda because it is flexible. We want your input on what you think are the important issues to address and how to address them. Thus, please feel free to suggest additions or deletions, we only have one day and we want it to be productive. If you want to send out information to other participants such that we can get a heard start, that would be welcomed also.

We anticipate that the product of this workshop will be a focused/condensed “white paper” on induced seismicity that the various government agencies will use to help them guide their future technology and research programs.

Last but not least, the output of previous similar workshops was used to develop a protocol for addressing induced seismicity issues for EGS. This is not the intent of this workshop, but undoubtedly the information and results of this workshop will affect the modification and creation of current and future protocols.

WORKSHOP ON INDUCED SEISMICITY

STANFORD UNIVERSITY
Bechtel Conference Center
February 4, 2010

AGENDA

7:30 AM Participants Arrive – Breakfast

8:00 Welcome and Introductions – Ernie Majer

Motivation of workshop, Purpose and Objectives, structure of workshop, brief overview of past workshop's results.
Anticipated products of current workshop

8:30 Review of Past Cases of Induced Seismicity (Mining, Waste Injection, Reservoir Impoundment etc) and How Risk has been assessed and dealt with - A. McGarr/J. Ake

Discussion on elements needed for risk assessment for induced seismicity and what are the main areas of uncertainties for induced seismicity?

10:00 Presentations by Attendees of Sample Current Induced Seismicity Project's Goals and Results

The purpose of this session is set the stage and background for the rest of the day in order to focus on the most critical issues for induced seismicity. Therefore, the emphasis should be on describing what is(or has) preventing(ed) the project from understanding and reaching its goals and what is (was) needed to make the project successful. For example, better fundamental knowledge, better subsurface characterization, understanding of physical/chemical processes, etc. or is it just a matter improved processing of the data we have?
(5-10 minute presentations each)

A. EGS
- Basel/Landau – H. Rueter
- The Geysers – D. Oppenheimer
- GEISER – R. Gritto
- Cooper Basin – H. Asanuma

10:45 Break

11:00 B. CO_2 Sequestration
- J. Rutledge

C. Oil and Gas
1. Stump
2. Frohlich

11:45 Summary of morning events – Charge for afternoon session – E. Majer

12:00 PM Working Lunch
Discussion of Public interactions and community Issues
Review of current practices and future needs – R. Baria

1:00 PM Discussion Session on Paths Forward

The afternoon will be devoted to identifying critical research and technology needs for induced seismicity. Hopefully, the morning has identified the gaps in our knowledge and technology that is needed to reduce uncertainty in the parameters needed to assess risk of induced seismicity. Thus the afternoon will be devoted to how to fill the gaps. The afternoon is structured with discussion leaders for three different areas. This is not intended to be a string of presentations (although bring a few slides with ideas) but discussions to identify critical research directions and technology for induced seismicity.

A. Lab and EQ Source Mechanism Studies
Discussion Leaders: N. Beeler /B. Ellsworth
B. Field and Instrumentation
Discussion Leaders: S. Hickman / M. Fehler
C. Theory/Modeling –
Discussion Leaders: P. Segall / A. Ghassemi

5:00 PM Summary of Discussions and Wrap Up

Next Steps and Follow-on Activities, Other Items

5:45 PM Working Dinner

WORKSHOP ON INDUCED SEISMICITY

STANFORD UNIVERSITY
Bechtel Conference Center
February 4, 2010

Attendees List

	Participants	Institution
1	Hiroshi Asanuma	Tohoku University
2	Horst Rueter	HarbourDom
3	Brian Stump	Southern Methodist University
4	Paul Segall	Stanford
5	Mark Zoback	Stanford
6	Jim Nelson	WIAI
7	Cliff Frohlich	University of Texas
8	Jim Rutledge	LANL
9	Roland Gritto	AIT
10	Roy Baria	MIL-TECH UK
11	Steve Hickman	USGS
12	Ernie Majer	LBNL
13	Art McGarr	USGS
14	Bill Ellsworth	USGS
15	Dave Lockner	USGS
16	David Oppenheimer	USGS
17	Peter Henning	Conoco-Phillips
18	Anca Rosca	Chevron
19	Brian Hornby	BP
20	Herb Wang	University of Wisconsin
21	Nick Beeler	USGS
22	Ahmad Ghassemi	Texas A&M
23	Mark Walters	Calpine
24	Ann Robertson-Tait	Geothermix
25	Peter Dracos	Ormat
26	Mike Fehler	MIT
27	Ahmed Abou-Sayed	ATI
28	Jon Ake	Nuclear Regulatory Commission
29	Oleg Vorobiev	LLNL
30	Bruce Julian	USGS/Foulger Consulting

Observers	Institution
Avi Gopstein	DOE
Arlene Anderson	DOE
Alison Labonte	DOE
Hildigunnur (Hidda) Thorsteinsson	DOE
Allan Jelacic	NWT
George Guthrie	DOE/NETL
Ben Phillips	NSF
Maryann Villavert (scribe)	LBNL
Doug Blankenship (scribe)	SNL
Mack Kennedy (scribe)	LBNL
Jim Berryman	LBNL
Pat Dobson (scribe)	LBNL
Colin Williams	USGS
Don Juckett	AAPG
Hamilton Hess	FOCM
Gillian Foulger	Alta Rock
Sue Petty	Alta Rock
Joe Iovenitti	Alta Rock
Melinda Wright	Calpine
Ali Kahn	State Ca

ATTACHMENT 2: Summary of February 4 Sessions on Induced Seismicity (E. Majer)

We would like to thank all that attended and participated in the meeting, as well as the sponsors DOE/Geothermal and the IEA. In addition, we would like to thank Roland Horn for help in providing the space at Stanford, and Steve Hickman for helping in the organization.

You should all be congratulated for the lively exchange of ideas and presentations; it made the meeting interesting, and created a momentum to move forward in addressing this topic which is very important to the success of not only geothermal energy, but also carbon sequestration and oil and gas applications.

Summary notes of the meeting and the "raw" reviewed (the participants were asked to correct, or add things that were missed in the notes):

Introduction: Ernest Majer

1. Induced seismicity has stopped several projects and could stop more. Congress, DOE and regulators are very concerned.
2. DOE/IEA addressed IS issues in 2004-2006, but recent events point out the need to expand efforts.
3. Must be able to provide technical and scientific basis of risk assessment and be able to address key questions to the satisfaction of regulators and the public, for example,
   a. What is the largest earthquake expected?
   b. Will small earthquakes lead to bigger ones in the same area?
   c. Can induced seismicity cause bigger earthquakes on distant or faults in the vicinity?
   d. Can induced seismicity be controlled?
   e. What controls are (will be) in place to mitigate future induced seismicity?
   f. What is the plan if a large earthquake occurs?
4. The above questions lead to a variety of technical and fundamental questions:
   a. For a critically stressed fault, will a pore pressure increase at a shallow depth trigger slip at the depth of the naturally occurring events?
   b. If so, what are the physical processes by which the slip at depth would occur?
   c. What bounds could be put on the magnitude of such an event?
   d. Does induced seismicity follow Omori's law?
   e. What controls the decay of seismicity after injection?
   f. Radius of influence (how close to a critically stressed fault can one be?)
   g. If "natural seismicity" is known to occur deep, how can one safely inject shallow?
   h. What are the similarities and differences between natural and induced earthquakes?
   i. What is the relation between foreshocks, aftershocks, b-values, etc?
   j. Will risk assessment be based on past seismicity, "physics" or some combination?
   k. What are the relevant and important physics and chemistry, and what key parameters do we need to determine to model processes at the appropriate scales? (scaling) What is the degree of coupling among the parameters?
   l. How can we correctly interpret geophysically-based diagnostic signals (microseismic), to help control the injection of fluid which is needed to stimulate the reservoir?
   m. Can we use this knowledge to manage induced seismicity?
   n. What controls the long-term reservoir performance? Can we establish methods to sustain it using the information from seismicity?

o. What are the “basic” properties of a site that are required for design and can we measure them? What technology is needed to measure required parameters?

5. Outreach to the community is critical, one must consider their concerns and address properly.
6. Objectives of the work shop
   a. Identify critical technology and research needs/approaches to advance the understanding of induced seismicity associated with injection and production, such that:
   b. The risk associated with induced seismicity can be reduced to a level that is acceptable to the public, policy makers, regulators and operators, and
   c. The seismicity can be utilized/controlled to monitor, manage and optimize the desired fluid behavior in the subsurface in an economic manner.
   d. Address the hypothesis: With proper study and technology development induced seismicity will not only be mitigated but will become a useful tool for reservoir management.

Art McGarr

1. Summary of several IS cases outside of EGS, CCS and Oil and Gas.
   a. Mining. Needed better data, better public outreach and information.
   b. Reservoir impoundment: Correlation between radius of influence and seismicity?
   c. China earthquake, (killed 200,000 people) was it induced? still not conclusive.
2. Questions/issues discussed
   a. Will redistribution of stress concentration allow more seismicity in some areas and inhibit in others
   b. Stress drops: what were they, how did it relate to observed displacement? (in mines)
      - What type of monitoring should be used in this case? Discussion – in retrospect what should have been measured
        - Monitoring of smaller EQs
        - What is the tipping point for stress increase?
          - Suggested 0.01 MPa is enough
          - Can models resolve this?
          - Look for the sign of the change? Will it make it better or worse?
          - What is there and is it big enough to cause a problem?
          - Are you advancing the clock or causing something that would not have normally occurred
   c. Does rate of injection makes a big difference?

Jon Ake

1. Regulatory context, EPA may be responsible in the long run for IS regulations.
2. Such issues as: in CCS will cap rock be damaged with IS, well integrity, as well as excessive ground motion, ground water contamination, etc
3. Loss of public trust, once it is lost it is very difficult to get back
4. Risk is a product of three things (frequency of occurrence) x (probability of occurrence) x (consequence of occurrence) i.e. the “Triad”.
5. In induced seismicity for the subject cases, what is the “delta” risk due to injection/production activities?
6. Estimating the Max Magnitude (ground motion) is critical.
7. Must be able to reduce the variance on all three elements of the risk triad or risk estimate is worthless, i.e, large uncertainty in any one of the three is bad!!

8. Discussion of Risk: Adhere to existing regulation on damage due vibration from mining, construction, etc? Even sleep disturbance is a reason to mitigate.. Can geothermal, CCS, oil and gas reasonably be expected to control seismicity? If not how does one reduce risk?
9. Difficult to quantify "acceptable risk", must take a variety of factors into account, both tangible to intangible. May vary from site to site.
10. Must have good baselines, longer the better!!
11. Rocky Mt Arsenal and Paradox Basin (PB)
    a. Mag 5.3 at Denver, 4's at PB, There was seismicity at Denver (Front Range) but not much at PB before injections.
    b. Needed better characterization!! At both sites. Better monitoring for source mechanism studies.
    c. Decrease of b-values, indicator of bigger events?
    d. Large radius of influence of injection along existing faults
    e. Mitigated by reducing rate of injections.
    f. A threshold of injection before large seismicity? Radius of influence?

<u>Horst Rueter</u>

1. Landau/Basel (note there is quite a lot of detail in Horst's presentation that he did not present, also a presentation By Serge Shapiro was included that was not presented).
2. Landau is a horst and graben structure with low background seismicity compared to Basel.
3. Different fault structures and there is a history of oil production at Landau.
4. Background seismicity b-value of .99, max mag 4.0, during injection b-value of 1.7.
5. Needed better velocity models (background characterization) and better MEQ monitoring
6. At Basel there were big event all over the place before geothermal project, should have been a clue to go slow on injection.

<u>David Oppenheimer</u>

1. Monitoring began in 75, many stations improved
2. Seismicity grew as production expanded.
3. M3s pretty constant since 85, M4s increasing, smaller events show good correlation between injection and production
4. All seismicity is induced, No M3 before 1975, EQs on small randomly oriented fractures 10000 EQs/ year; 1000 m>1.5
5. Residents are very knowledgeable and there has been damage reported in area
6. Subsidence at rates of up to 4 cm/year, but average more on the order of 2.5 to 3 – over a meter in some areas.
7. Subsidence is very high, anomalous, INSAR images hot spots may due to landslides?
8. What now? Great location to study, lots of events, lots of data, deformation data, model, Collaboration between Industry and researchers needed.

<u>Roland Gritto</u>

1. Two Projects (see PPT presentation): Many of the objectives of these two projects are the same as the needs identified in this workshop.

US Geysers

Develop techniques to evaluate relationship between operations and seismicity.

a. Relationship between activities and large events M3, M4
b. Why does large seismicity increase over time?
c. Triggering or inducing, what is largest possible event?
d. Techniques, 4-d,.Full waveform moment tensors, Geomech analyses of steam production/injection to model stress evolution, Estimation of Seismic hazard and calc of ground motion.

2. GEISER – EU - "soft Injection"

a. Similar goals, 7 participating countries (including Iceland), Review 11 Geothermal datasets. Similar work plan but will include lab testing.
b. US and EU Project are partner projects All participants have access to data AIT will pass data to DOE

Hiro Asumama

1. Cooper Basin
   a. 20000 m^3 injected
   b. Moment Magnitude, Large = > 1, Up to about M3 measured No obvious correlation to WH pressure?
   c. Locations distribute to edges of cloud
   d. BE (big events) similar in character to small events
   e. BE after shut in observed, No pre – shocks, yes after shocks
   f. BE improve permeability

2. Oku-Aizu
   a. 65 MW plant since 90s
   b. Most events during production <2, around 2001 a M4.6 measured
   c. Believed related to production

Jim Rutledge

1. Monitoring during CO2 injection in the Aneth Oil Field
   a. Seismicity detected immediately – but direct association with CO2 injection is not evident. CO2 injection occurs uniformly across the field. The seismicity reveals isolated structures on or near flanks or reservoir.
   b. In general seismicity should be expected during CO2 sequestration, and should be a useful tool in tracking fluid movement. Monitoring seismicity will be most critical for detecting and locating fault activation and identifying potential leakage of CO2 from a target reservoir.
   c. Aneth field: Water flooding since the 1960s. Conversion to CO2 injection in study area just recently.
   d. Only one geophone string deployed for study, needed more geophones in wells for better field coverage
   e. Does not think the conversion from water to CO2 has had an effect on the seismicity.

f. Appears to be a rough correlation between salt-water injection below the reservoir and seismicity; however location of events and location of injection indicate this would be hard to reconcile. Salt-water injection rates though are a proxy for field wide extraction rates from the oil reservoir, so the seismicity may be the result of field-wide production, not injection.
g. A Mag 3.6 event occurred during monitoring, 8 miles outside the field. Difficult to prove whether it was induced or not induced. Depth is poorly constrained. Time of event correlates with increased oil production and increased microseismicity rates in the reservoir.

<u>Cliff Frohlich / Brian Stump</u>

1. Two induced seismicity cases
   a. 2008, Oct 31 - EQ in DFW, M3.0 May 2009 – M3.3
   b. July in Cleburne TX, M3.3
2. Barnett Shale heavily produced since 2002
3. Sparse seismological coverage, SMU borrowed seismographs – Dec 2008
4. Location in a very small 1 km^2 straddles mapped fault EQ depths 4.5
5. Disposal well in same location (disposal depth 3.3 – 4.2 km)
6. Related to disposal, not production (not due to hydrofractures)
7. Disposal started in Sept, 7 weeks later EQs began. Disposal about 10,000 bbl/day.
8. Data does not seem to correlate to hydraulic fractures in the local area, but that may be a possibility.
9. June 2, 2009 event in Cleburne
   a. Event location between two injectors
10. Need to delineate between drilling, hydrofracting and disposal
11. Communication to public
12. Why do some wells have IS and the great majority do not.

<u>Hamilton Hess (see handouts)</u>

1. Property owner since ‘39
2. Lives on the edge of the field
3. Representing the Anderson Springs Community alliance
4. Seismic Monitoring Committee serves as a potential model for other similar locations Established by Lake County BOS
5. IEA-GIA slogan not acceptable
6. They are not against Geothermal, but Community is upset over continued seismicity.
7. Protocol needs to incorporate mitigation and limitations

Summary of Morning Sessions

Main Themes

1. Need better data in time and space. Many noted the need for better characterization overall of the geology, faults, stress and details of the seismicity before and during (after if it has stopped) injections for source mechanism studies, energy release versus reservoir parameters
2. Stress field: How well do we need to know it? How well can we know it? Knowing the stress field (in addition to good characterization, i.e. where are the faults, geology, etc.) seemed to be central estimating seismic potential.
3. Standardization of processing methods? Methods are not lacking, however, knowledgeable personnel must be using software.
4. Risk: What is the acceptable risk? How do we determine it? What is acceptable seismicity?
5. Geologic models: How good do they need to be?
6. Most CO2 injection studies to date have been in context of EOR operations where CO2 injection follows decades of water flood injection and pressure recovery operations, making it difficult to interpret the effect of CO2 injection.
7. Did not hear: Do we really understand what is going on? Do we need more fundamental work (rock physics, chemical and physical interactions) to understand and mitigate IS?
8. Do we need dedicated test sites? How do we drive the system to failure at industry sites? Can one collect all the necessary data and do necessary manipulative experiments at an industry controlled site? What can be done at industry sites?
9. Scaling (lab to field): How do we take information at the lab scale and extrapolate to the field scale?

Afternoon Discussion Sessions
(In the interest of time, the three afternoon sessions were combined)

Bill Ellsworth/Nick Beeler: Barriers and needs to understanding mechanics of fault failure

Steve Hickman/Mike Fehler: Field considerations and needs

Paul Segall/Ahameed Ghassemi: Modeling and Laboratory studies

---

1. Probabilistic Seismic Hazard Analyses: What is needed and what is the difference between current PSHA for "natural" seismicity and induced seismicity?
2. Uniform CA EQ Rupture Forecast currently use Fault Models, Deformation Models, EQ Rate Models, Probability Models
3. The main question is: Can you move the current models used for natural seismicity to model to the small scale of reservoirs, i.e. in the current practices replace the deformation models with a valid stress model. To do this one will need accurate Fault Models, Stress Models, and EQ Rate Models and Probability Models (related to perturbations)
4. Question to address are:
    a. Does knowledge of reservoir and surrounding rock mechanics properties (rock strength, fault strength, permeability, porosity, poroelasticity) tell us anything about susceptibility to induced seismicity
    b. Does induced microseismicity reflect changing rock mechanical properties in an interpretable way?
    c. Does reservoir stimulation increase fault susceptibility to seismic slip?
    d. Does rock failure (from hydrofrac/hydoshear) have any bearing on induced seismic hazard or is all the hazard in reactivated events?
5. Critical in getting to probability model. Does reservoir knowledge and rock mech tell us about susceptibility to induced seismicity?
6. Must be careful, if risk is not done properly it would be a recipe for disaster. i.e.
    a. Regional tectonic stress near fault failure strength
    b. Large fault intersects reservoir
    c. Large fault close to optimal orientation
    d. Fault is permeable along strike or small scale fault slip on large fault allows reservoir to expand along strike
    e. Pressure in large fault exceeds failure strength
7. Candidate Fault Mechanics Research Needs
    a. What limits the magnitude of induced earthquakes (size of pressurized zone, length of fault)?
    b. Do we need better knowledge of relation between stress change (particularly effective normal stress) and seismicity rate?
    c. Is there time dependence or stressing rate dependence in stress-seismicity rate changes? Or is the theory of effective stress all we need to know?
    d. Do we need to know slip-dilatancy (slip-permeability) relations better for fault zones?
    e. Do we care about hydrothermal processes (fault healing, permeability reduction) in the induced seismicity problem?
    f. Do we need to know more about fault zone poroelasticity?
    g. Do we need to know more about chemical processes?
    h. Do induced earthquakes follow the same attenuation relations as tectonic earthquakes in the same province?

What is keeping us from answering important questions?

1. Need observation wells
2. Need Experimental Sites
3. Sites need to be very well Characterized
   a. Laboratory testing
   b. Rigorous establishment of baseline stress

Discussion on timing of experiments at a dedicated test site,

If you wait for complete information, will you ever start? Can you start, start with current data and fill in needs with test sites? Lots of data in O&G on activation of faults (But do they have all the background data needed)

If proprietary data were more available we may not need new fields – not just O&G but get data from the existing geothermal fields. In O&G companies do not want to share data with companies near their competitors. Solve problems with GOV-Private partnerships.

Are we thinking too small? Why not perform active in situ experiments to examine the effect of perturbations on the system. Need field scale tests to examine specific questions

Issues to consider in a dedicated field site

1. Research projects with unlimited budgets are good but it needs to be scaled down to deal with the reality of actual projects if it is to benefit development of projects
2. Piggyback on existing projects – Industry should be welcoming this participation
3. What does the research community need to do to interface with industry?
4. If you are going to do a field test, what scale should be chosen
5. Do the observations support the models, what can't we measure in a meaningful way
6. Not everything needs to wait on the Cadillac projects – can get something form the projects in hand
7. Industry Perspective. All companies are focused on the Induced Seismicity issue and a receptive audience would be found.
8. The DOE's Regional CO_2 Sequestration Partnerships are now entering their Phase III projects where larger scale injection into saline aquifers (up to 1M tons per year) will be taking place. Some of these projects could provide excellent opportunities to study induced seismicity in field settings that have not been complicated by a history of fluid extraction and injection operations as one finds in O&G and EGS projects.
9. The caveat with the CO_2 projects is the lack of data to start with, but the characterization that will be required for assessing risk and designing CO_2 projects should also benefit and include the evaluation and study of induced seismicity.
10. Studying induced seismicity under CO_2 projects would also be attractive in developing and testing downhole instrumentation outside the challenge of high temperature environments.

Key questions and issues

What needs to be done?

1. Know stress
2. Fracture distributions/ orientations
3. Fluid loss zones
4. Rock properties (lab testing)
5. Correlation to lab tests with geophysics
6. Modeling needs
   a. Analytical models to test effects for validation of numerical codes
   b. Advanced computational infrastructure
   c. Experimental data
7. Field tests
   a. Test thermal stressing effects
   b. Injection rate dependence
   c. Injection cycling

Field Wish list (geothermal specific = HT needs)

1. Need HT open hole packers
2. Continued development and commercialization of HT imaging tools
3. More robust tools for damaged/rough holes and muds (all applications)
4. High-T, low flow, flow meters
5. HT dipole sonic tools (full wave form)
6. HT Seismic characterization tools (for VSP and fracture imaging at Reservoir level, multilevel tools that can be retrieved)
7. Detailed seismic monitoring in boreholes (implies cheap drilling methods and borehole instrumentation (need not need be high temp if stay above high temp zone in geothermal applications) for "permanent " installation (all applications)
8. Reliable (accurate zero times and monitoring) of calibration shots in boreholes (all applications) (need HT for Geothermal)
9. Processing and analysis needs
   a. Moment tensor inversions
   b. Stress analyses for extrapolation beyond the hole
   c. Improved tomographic methods for special and temporal variations in fluid pressure / fracture density / anisotropy
10. Development of improved deformation monitoring techniques
    a. GPR
    b. InSAR
    c. Tilt meters (most of the deformation accompanying injection occurs aseismically. The question of whether seismic deformation is double couple or non-double couple becomes irrelevant when you consider what a small fraction of the deformation the seismicity represents. Thus, far-field measurements of strain changes are needed as warning systems and to provide input for models. A reliable microhole tiltmeter or strain gauge would be ideal. Developing this for EGS applications (high T) would be particularly challenging.
    d. Combine Seismic with fluid sensitive methods (EM)

Laboratory Testing Needs (note: in geothermal cases need high temperature also)

1. How does fracture permeability and fault strength evolve at geothermal conditions?
2. Permeability evolution using rotary shear testing
   a. Effect of large shear displacement
   b. Gouge production
   c. Development of fines
3. Mechanical properties testing needed to understand relationship between rock properties and fracturing / shearing results
4. What are the effects of chemical processes in modifying fracture permeability and fault strength over time scales equivalent to a reservoir
5. Discussion – reservoir model that includes mechanics associated shearing is needed - lab testing is needed.

Discussion on possible mechanisms for induced seismicity

1. Well scale
   a. Effective stress changes
   b. Poroelastic effects
   c. Thermoelastic effects
   d. Lag in seismic response indicates rate dependence
2. Reservoir scale
   a. Thermo-poroelastic effects
   b. Chemical effects
   c. Interactions among all phenomena

Discussions at end

What are the advantages of working at different depths (near surface versus at depth) Testing at all scales is needed. Can one take the European example and translate that experience to the US? A lot of money has been spent but are the past examples applicable to the enhancement of existing hydrothermal systems (all funded projects by DOE). Will this experience provide the community any comfort? Are simple slip solutions appropriate for complex hydrothermal systems? Perhaps data sets for Geysers should be evaluated to determine if examining the assertion about learning from the European experience holds true for other locations. Need balance between the industries.