ISC Annual Report- Summary

Table of Contents

Section 1: Executive Summary **2**

Section 2: Hydraulic Fracturing Case Study: Bowland Shale, Blackpool, United Kingdom **4**
- Summary 4
- Introduction 4
- The Bowland Shale and Seismic Events 5
- Geology and Faulting 6
- Treatments 8
- Results and Recommendations by Different Agencies 9
- Trends and Relationships 9

Section 3: Wastewater Disposal Injection Case Study: Youngstown, Ohio **13**
- Introduction 14
- Background Information 14
- Purpose 15
- Goal 15
- Methods 16
- Results and Discussion 17

Section 4: California Project

a) Seismicity in the Oil and Gas Fields Case Study: California **19**
- Summary 19
- Introduction 19
- Data 20
- Earthquake Facts 23
- Preliminary Observations 25
- Seismicity Statistics and Prediction Studies 31
- Probabilistic Hazard Forecast 38
- Correlating Seismicity with Field Operation Parameters 39
- Data Mining 39
- Monitoring Software Design 41
- Results from Monitoring Software 42
- Conclusions and Future Work 46
- References

b) **Identifying induced seismic events in active tectonic regions in San Joaquin Basin, California** **47**
- Summary 47
- Background 47
- Method and Data 48
- Results 49
- Discussion 56
- Future Research 57
- References 57

Section 5: Additional Accomplishments
Analysis of Injection Related Seismic Hazard in Prague, Oklahoma 60
The Monterey Shale & California's Economic Future 62
Hybrid Micro-Seismic Survey Design 68
Geomechanical Modeling for the Analysis of Induced Seismicity 69

Section 6: Public Outreach **74**
RPSEA, Pennsylvania
South California Air Quality District, Diamond Bar
PTTC, Cleveland, Ohio
ERC, Washington DC
Science Center, Los Angeles
Water Conference, San Diego
AGU, San Francisco

Section 7: Looking Forward **75**

Appendix A: Strategic and Technical Advisory Boards **77**

Appendix B: Publications and Presentations **78**

Appendix C: Fault Activation Studies in the Laboratory **83**

Section 1: Executive Summary

The Induced Seismicity Consortium (ISC) was organized in late 2012 to address the very critical and underdeveloped aspects of environmental safety and seismic impacts associated with subsurface fluid injection and production processes (SFIP). Broadly, SFIP operations include hydraulic fracturing (hydrofracking), wastewater injection disposal wells, fluid production, geothermal resource development, enhanced oil recovery (EOR), and carbon capture and storage (CCS). A collaborative partnership was thus formed between scientists from different programs at the University of Southern California with industry and government agency partners to address two main goals in regards to SFIP safety: 1) to advance geoscience and engineering technologies required to predict geologic and surface impacts of SFIP, and 2) effectively communicate with, inform, and advise regulatory, educational, and public entities with regards to SFIP operations and impacts.

The multidisplinary approach within the ISC is well poised to examine available data and develop predictive models to assess seismic impacts associated with SFIP operations. Therefore, the ISC originally identified seven specific tasks aimed to accomplish these objectives. They include: 1) the characterization of fracture networks with microearthquake data, 2) establish correlations between induced earthquakes and microseismic attributes, 3) develop a hierarchical probabilistic model to understand the relationship between operational parameters, subsurface stress, and observed seismicity, 4) design a system to mitigate the seismic hazards associated with SFIP, 5) provide a regional geologic framework for the interpretation of observed seismicity and predictive models, 6) create a science-based framework for input to regulatory and government entities, and 7) introduce educational and communication programs for the professional community and the general public.

Some of ISC goals specifically address the concerns brought forth by the 15 June 2012 National Research Council report on induced seismicity, which concluded that research is needed to build robust models to predict and assess potential seismic hazards, and help relevant agencies to address them. As a collaborative partnership, the ISC focused specifically on factors that affect the initiation, location, magnitude and mechanisms associated with induced seismicity. The core of this challenge is to use research tools to explore the fundamental science with respect to induced seismicity, and to effectively communicate the findings to regulatory agencies and the general public.

The ISC thus laid out initial plans to investigate and predict the potential for noticeable tectonic (natural) earthquakes, as well as examine the possibility for failure in SFIP operations. Recommendations provided by industry and academic partners, respectively, identified and finalized specific priorities and deliverables for the ISC. Based on the recommendations of the Strategic and Technical Advisory Boards (Appendix A) during their second quarterly meeting, the ISC identified three main target sites for investigation, which included: 1) observed microearthquake activity possibly related to hydraulic fracturing in the Bowland Shale of Blackpool, United Kingdom, 2) earthquake activity possibly related to wastewater injection in Youngstown, Ohio, and 3) examine seismicity associated with oil and gas fields in the state of California.

This report highlights the accomplishments in those three areas and fulfillment of those tasks. In Section 2, we highlight fifty earthquakes that are potentially associated with hydraulic fracturing in Blackpool, United Kingdom, including two events in 2011 of M1.5 and M2.3, respectively. We conducted this study to examine the relationship between hydraulic fracturing and seismicity observed in the Blackpool region, and generate a geomechanical model with various parameters that could potentially cause the observed seismicity, with the goal to establish a temporal relationship to forecast earthquake activity based on the time lag between seismic events and change in bottom-hole pressure.

In Section 3, we examine seismicity possibly related to fluid injection in Youngstown, Ohio. Youngstown, Ohio is a relatively stable portion of the continental interior of the United States, thus historic earthquakes are rare within this region. Previous studies suggest that the NorthStar #1 disposal well, which is placed within close proximity of the earthquake activity, may have induced these events on a previously unknown fault system. Therefore, wastewater injection in this region may have reactivated this fault. The goal of this study is to use known seismic data to understand the geologic properties of the formation (i.e. perform tomography), and examine whether the earthquakes can tell us something about the fracture network and permeability of the formation.

In Section 4, we demonstrate a method to differentiate between tectonic and induced seismicity in the state of California, within a region of many known and active geologic faults. We have analyzed seismicity recorded between January 1980 and June 2013, in regions around three major California Basins: Los Angeles Basin, San Joaquin Basin, and Sacramento Basin. Many wells have been completed in these regions which exist within the vicinity of major fault zones. We have built new seismic monitoring software to correlate hydraulic fracturing jobs and other oil field activities with the recorded seismicity. In addition, we have shown that frequency-magnitude (or b-value) analysis could be useful tool to determine whether seismicity is induced or tectonic, with careful investigation. Our statistical and modeling results delineate that oil field operations may not cause M4 or above earthquakes in the absence of fault-related seismicity. In addition, we have initiated a new study in which we will focus on the assessment of the reactivation potential of faults due to fluid induced pressure and stress changes. This is especially of interest in regions of high seismic activity and known large historic earthquakes, and will aid to minimize the seismic hazard connected to anthropogenic influences within the study region.

Finally, in Sections 5 and 6, the report highlights other accomplishments both in technical areas and public outreach, and in Section 7, proposed areas of new activities. We value your continued support of the ISC, and we encourage new members to join with us to expand our investigation of environmental and seismic safety associated with SFIP operations. We invite you to discuss specific tasks and goals to meet your objectives, and ask for a list of your high priority action items for discussion during the Advisory Board Meeting on 23 October 2013.

Section 6: Public Outreach

RPSEA, Pennsylvania
South California Air Quality District, Diamond Bar
PTTC, Cleveland, Ohio
ERC, Washington DC
Science Center, Los Angeles
Water Conference, San Diego
AGU, San Francisco

Section 7: Looking Forward

As the first year of the Induced Seismicity Consortium draws to a close, we examine our past accomplishments with this report, but also take an opportunity to look forward to additional areas of growth for future endeavors. We thank our generous sponsors and Strategic and Technical Advisory Boards for providing us with guidance in past projects, and we value your continued expertise for the future. Furthermore, as the ISC continues to develop and expand, we consistently recommit ourselves to the overall mission to find new techniques and methods to improve the environmental welfare and seismic safety associated with subsurface fluid injection and production processes.

We will use the input from our existing and new sponsors to enhance our research and development activities. We encourage such input before and during the Fourth Quarterly meeting. As it stands right now, based on the feedback received thus far on the original goals of the project, as well as results during the first year, we propose the following preliminary future directions:

1. **Youngstown, Ohio Project.** We will build on the past accomplishments of this project to advance data analysis and tomographic inversion. This (and many other tasks) will be of higher technical content, thanks to the addition of an exceptional seismologist as a post-doctoral fellow to our team (Dr. Danielle Sumy). In addition, she is able to access previously unavailable datasets and algorithms, and has the expertise to seismically examine the subsurface structure with use of tomography.
2. **California Project-** We continue our work regarding oil and gas fields in California, with the ultimate goal to analytically correlate reported operational parameters with induced events and delineate reasons why this is the case. In addition, we focus on an assessment of reactivation potential for faults due to fluid induced pressure and stress changes. This is of specific interest in regions of frequent seismic activity and large magnitude (M>7) historic earthquakes in close proximity to urban populations, and will aid to minimize the seismic hazard connected to anthropogenic influences within the study region.
3. **Oklahoma Seismicity Project**- Among new research directions is a project to investigate the magnitude and intensity of earthquake-generated shaking in Prague, Oklahoma, in an effort to improve seismic hazard maps in the region. This study will allow for an improvement of seismic hazard in a region where three M>5.0 induced earthquakes were identified in November 2011, and thus allow for more comprehensive insight into the role injection plays in seismic hazard, a key task for the ISC. Furthermore, an additional project funded by a GTI grant is aimed at understanding the elements which influence the design of multi array passive seismic monitoring programs and to develop a framework for optimization of such arrays for improved hypocentral locations and source mechanisms, while still optimizing deployment costs.
4. **Geomechanical Modeling for Microseismicity-** We will focus on two main subject areas of (1) better understanding of the mechanisms by which induced seismicity is generated, and (2) assessing microseismic risk.

    a. We thus will apply the current GSBRC to a case of hydraulic fracturing in a homogeneous isotropic reservoir to come up with the closed form solutions which describe the mechanism behind microseismic activities associated with hydraulic fracturing. The main difference between this study and our previous studies will be the difference in the pressure diffusion equation, as well as incorporating the effect of stress shadow around a hydraulic fracture.
    b. We expect to extend the current GSBRC model to a heterogeneous anisotropic reservoir. As such, we will develop input to Eclipse or other flow simulators to model pore pressure associated with a permeability distribution in the reservoir. The permeability realizations will be updated to match the observed microseismicity in the reservoir based on the geomechanical model. Using the forward model one can model the Coulomb stress change and associated seismic risk.

5. **Laboratory Test to Analyze Fracturing and Fault Activation-**As part of our future research efforts, we propose to study fault activation and generation of new fractures due to fluid injections in laboratory experiments. This line of research has the potential to provide insight into the natural and fluid induced faulting processes and provides means to document source processes and fault structures under seismogenic conditions. We expect to conduct this work in collaboration with the rock deformation and rheology laboratory at GFZ-Potsdam. See Appendix 3 for more details.

6. **Developing Surveys for Real Time Seismic Monitoring-** In many cases, the analysis of our induced seismicity work in the oil field is hampered by the availability of properly designed surveys and data acquisition to monitor SFIP operation. We will identify at least one test site to install a low-cost seismic monitoring system. We will use the results in conjunction with existing seismic networks (usually at locations far from the oil and gas operation) to further enhance and validate our preliminary results.

Appendix A

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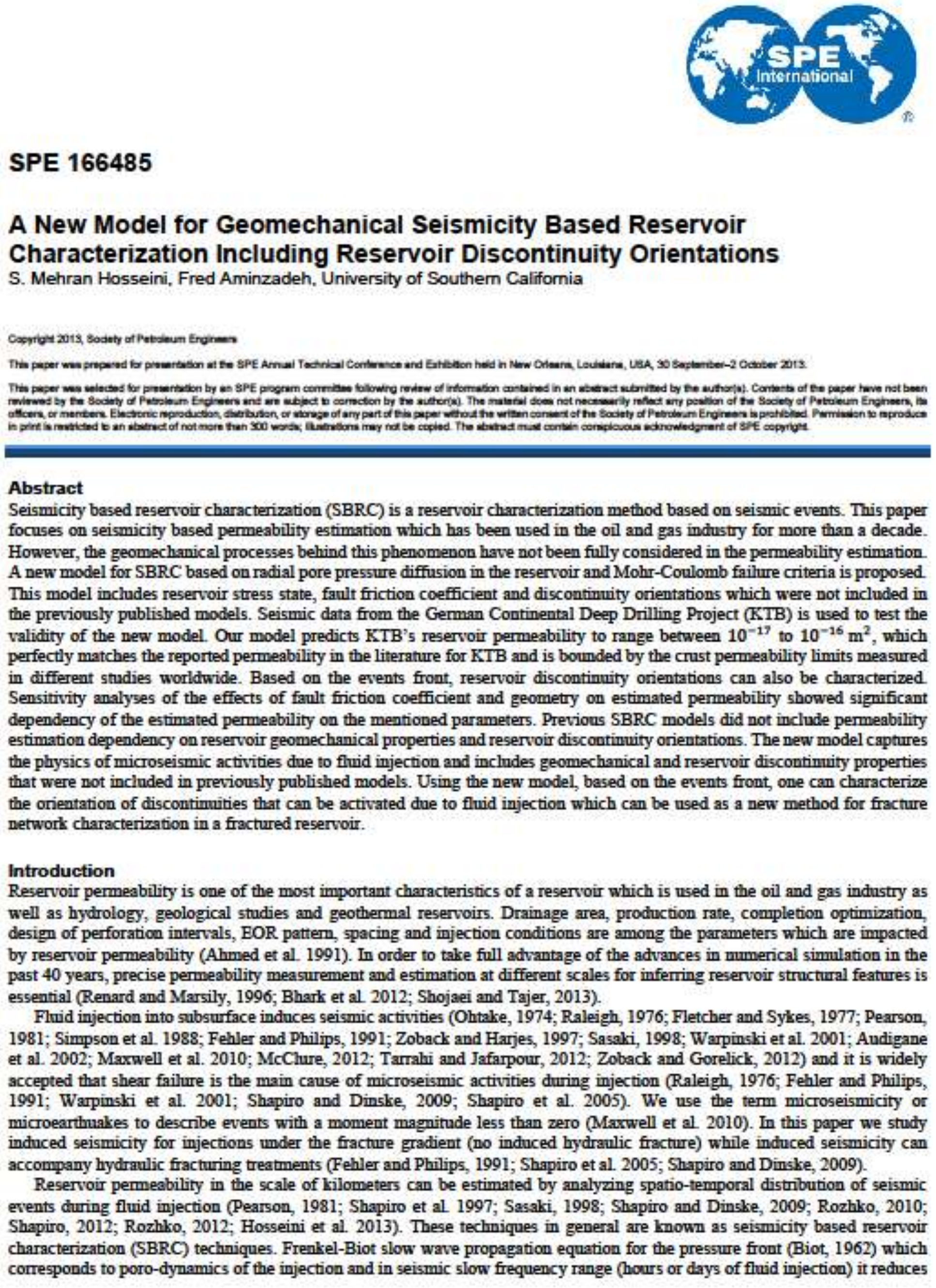
Appendix B: Publications and Presentations

This appendix provides the first page of all of our publcations directly or indirectly are related to ISC, during its first year or operation.



SPE 166485

A New Model for Geomechanical Seismicity Based Reservoir Characterization Including Reservoir Discontinuity Orientations

S. Mehran Hosseini, Fred Aminzadeh, University of Southern California

This paper was prepared for presentation at the SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, USA, 30 September–2 October 2013.

Abstract

Seismicity based reservoir characterization (SBRC) is a reservoir characterization method based on seismic events. This paper focuses on seismicity based permeability estimation which has been used in the oil and gas industry for more than a decade. However, the geomechanical processes behind this phenomenon have not been fully considered in the permeability estimation. A new model for SBRC based on radial pore pressure diffusion in the reservoir and Mohr-Coulomb failure criteria is proposed. This model includes reservoir stress state, fault friction coefficient and discontinuity orientations which were not included in the previously published models. Seismic data from the German Continental Deep Drilling Project (KTB) is used to test the validity of the new model. Our model predicts KTB's reservoir permeability to range between 10^{-17} to 10^{-16} m^2, which perfectly matches the reported permeability in the literature for KTB and is bounded by the crust permeability limits measured in different studies worldwide. Based on the events front, reservoir discontinuity orientations can also be characterized. Sensitivity analyses of the effects of fault friction coefficient and geometry on estimated permeability showed significant dependency of the estimated permeability on the mentioned parameters. Previous SBRC models did not include permeability estimation dependency on reservoir geomechanical properties and reservoir discontinuity orientations. The new model captures the physics of microseismic activities due to fluid injection and includes geomechanical and reservoir discontinuity properties that were not included in previously published models. Using the new model, based on the events front, one can characterize the orientation of discontinuities that can be activated due to fluid injection which can be used as a new method for fracture network characterization in a fractured reservoir.

Introduction

Reservoir permeability is one of the most important characteristics of a reservoir which is used in the oil and gas industry as well as hydrology, geological studies and geothermal reservoirs. Drainage area, production rate, completion optimization, design of perforation intervals, EOR pattern, spacing and injection conditions are among the parameters which are impacted by reservoir permeability (Ahmed et al. 1991). In order to take full advantage of the advances in numerical simulation in the past 40 years, precise permeability measurement and estimation at different scales for inferring reservoir structural features is essential (Renard and Marsily, 1996; Bhark et al. 2012; Shojaei and Tajer, 2013).

Fluid injection into subsurface induces seismic activities (Ohtake, 1974; Raleigh, 1976; Fletcher and Sykes, 1977; Pearson, 1981; Simpson et al. 1988; Fehler and Philips, 1991; Zoback and Harjes, 1997; Sasaki, 1998; Warpinski et al. 2001; Audigane et al. 2002; Maxwell et al. 2010; McClure, 2012; Tarrahi and Jafarpour, 2012; Zoback and Gorelick, 2012) and it is widely accepted that shear failure is the main cause of microseismic activities during injection (Raleigh, 1976; Fehler and Philips, 1991; Warpinski et al. 2001; Shapiro and Dinske, 2009; Shapiro et al. 2005). We use the term microseismicity or microearthuakes to describe events with a moment magnitude less than zero (Maxwell et al. 2010). In this paper we study induced seismicity for injections under the fracture gradient (no induced hydraulic fracture) while induced seismicity can accompany hydraulic fracturing treatments (Fehler and Philips, 1991; Shapiro et al. 2005; Shapiro and Dinske, 2009).

Reservoir permeability in the scale of kilometers can be estimated by analyzing spatio-temporal distribution of seismic events during fluid injection (Pearson, 1981; Shapiro et al. 1997; Sasaki, 1998; Shapiro and Dinske, 2009; Rozhko, 2010; Shapiro, 2012; Rozhko, 2012; Hosseini et al. 2013). These techniques in general are known as seismicity based reservoir characterization (SBRC) techniques. Frenkel-Biot slow wave propagation equation for the pressure front (Biot, 1962) which corresponds to poro-dynamics of the injection and in seismic slow frequency range (hours or days of fluid injection) it reduces

Identifying induced seismicity in active tectonic regions: A case study of the San Joaquin Basin, California

American Geophysical Union Annual Meeting, San Francisco, December 8-14, 2013

Fred Aminzadeh, Thomas H. W. Goebel

Understanding the connection between petroleum-industry activities, and seismic event occurrences is essential to monitor, quantify, and mitigate seismic risk. While many studies identified anthropogenically-induced seismicity in intraplate regions where background seismicity rates are generally low, little is known about how to distinguish naturally occurring from induced seismicity in active tectonic regions. Further, it is not clear how different oil and gas operational parameters impact the frequency and magnitude of the induced seismic events.

Here, we examine variations in frequency-size and spatial distributions of seismicity within the Southern Joaquin basin, an area of both active petroleum production and active fault systems. We analyze a newly available, high-quality, relocated earthquake catalog (Hauksson et al. 2012). This catalog includes many seismic events with magnitudes up to M = 4.5 within the study area. We start by analyzing the overall quality and consistence of the seismic catalog, focusing on temporal variations in seismicity rates and catalog completeness which could indicate variations in network sensitivity. This catalog provides relatively homogeneous earthquake recordings after 1981, enabling us to compare seismicity rates before and after the beginning of more pervasive petroleum-industry activities, for example, hydraulic-fracturing and waste-water disposals.

We conduct a limited study of waste-water disposal wells to establish a correlation between seismicity statistics (i.e. rate changes, fractal dimension, b-value) within specific regions and anthropogenic influences. We then perform a regional study, to investigate spatial variations in seismicity statistics which are then correlated to oil field locations and well densities. In order to distinguish, predominantly natural seismicity from induced seismicity, we perform a spatial mapping of b-values and fractal dimensions of earthquake hypocenters.

Seismic events in the proximity to active oil fields generally show different characteristics of frequency-magnitude distributions, higher fractal dimensions and higher b-values compared to natural seismicity. The estimated b-values vary between 0.7 close to the San Andreas fault up to 1.3 within the North-western corner of the Kern County. High b-values within this particular region are likely related to active petroleum production. The spatial differences in seismicity statistics delineate earthquakes related to active faults from distributed seismicity toward the center of the basin. Our results highlight, that the analysis of spatial and temporal variations in seismicity statistics may be a promising tool to identify induced seismicity in active tectonic regions.

The November 2011 M5.7 Oklahoma Earthquake: Induced or Triggered? American Geophysical Union Annual Meeting, San Francisco, December 8-14, 2013

Danielle F. Sumy*, Elizabeth S. Cochran, and Fred Aminzadeh*

On 6 November 2011, a M5.7 earthquake ruptured a ~N55E-striking trend on the Wilzetta fault in Prague, Oklahoma. This earthquake was preceded by a M5.0 foreshock that occurred on 5 November 2011 and followed by a M5.0 aftershock that occurred on 8 November 2011. Seismicity during the sequence delineates three, distinct near-vertical fault planes. The M5.0 foreshock was within several hundred meters of two active, high-volume injection wells, and thus was interpreted as potentially induced by *Keranen et al.* [2013]. Immediately following the M5.0 foreshock, three temporary seismometers were installed, with additional 44 stations installed after the M5.7 mainshock. These 47 stations recorded thousands of foreshocks and aftershocks that surrounded the three M≥5.0 events.

Induced seismicity from different subsurface fluid injection and production (SFIP) operations such as hydraulic fracturing, waste water injection and geothermal energy activities has become an important topic. Consequently, predicting any side effects of SFIP operations on the local stress field and fault system, including induced and triggered seismicity in naturally occurring faults would be valuable. Modeling and micro-earthquake data analysis can help establish the correlation between generated seismicity and the SFIP operations.

We examine the focal mechanism solutions of 110 events to further investigate the faulting in the region. Many of the focal mechanisms are consistent with the rupture planes defined by the seismicity of the foreshock and mainshock, which strike 207º and 54º, respectively. In addition, several focal mechanisms solutions exhibit dip-slip focal mechanisms and/or are most consistent with to the M5.0 aftershock, which occurred on a previously unmapped structure that strikes nearly 90º. These results suggest complex fault interactions within the Wilzetta fault system.

Based on these focal mechanism solutions, we investigate the static stress changes imparted on the aftershocks resulting from each of the M≥5.0 earthquakes. We find that the stress change induced by the M5.0 foreshock increases the stress at the hypocentral location of the subsequent mainshock. The combined stress change from the foreshock and mainshock, however, results in a static stress decrease at the hypocentral location of the largest aftershock. Thus, we find that while wastewater fluid injection may be to blame for the M5.0 foreshock, static stress triggering is responsible for triggering the mainshock.

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Hydraulic Fracturing and the Environment

American Geophysical Union Annual Meeting, San Francisco, December 8-14, 2013

Tayeb Tafti, Fred Aminzadeh, Felipe Barros, Behnam Jafarpour

In this presentation, we highlight two key environmental concerns of hydraulic fracturing (HF), namely induced seismicity and groundwater contamination (GC). We examine the induced seismicity (IS) associated with different subsurface fluid injection and production (SFIP) operations and the key operational parameters of SFIP impacting it. In addition we review the key potential sources for possible water contamination. Both in the case of IS and GC we propose modeling and data analysis methods to quantify the risk factors to be used for monitoring and risk reduction.

SFIP include presents a risk in hydraulic fracturing, waste water injection, enhanced oil recovery as well as geothermal energy operations. Although a recent report (NRC 2012) documents that HF is not responsible for most of the induced seismicities, we primarily focus on HF here. We look into vaious operational parameters such as volume and rate of water injection, the direction of the well versus the natural fracture network, the depth of the target and the local stress field and fault system, as well as other geological features. The latter would determine the potential for triggering tectonic related events by small induced seismicity events.

We provide the building blocks for IS risk assessment and monitoring. The system we propose will involve adequate layers of complexity based on mapped seismic attributes as well as results from ANN and probabilistic predictive modeling workflows. This leads to a set of guidelines which further defines “safe operating conditions” and “safe operating zones” which will be a valuable reference for future SFIP operations.

We also illustrate how HF can lead to groundwater aquifer contamination. The source of aquifer contamination can be the hydrocarbon gas or the chemicals used in the injected liquid in the formation. We explore possible pathways of contamination within and discuss the likelihood of contamination from each source. Many of the chemical compounds used in HF fluids are carcinogenic and may pose risk to humans. In addition, recovered HF fluids can be contaminated. We illustrate how different pathways can lead to the risk of aquifer contamination and consequently, risk to human health.

Induced Seismicity, The Science, Public and Regulation
Interstate Oil and Gas Compact Commission Annual Meeting,
Long Beach, CA, November 4-6, 2013
Fred Aminzadeh, and Donald Paul
University of Southern California

Hydraulic fracturing or fracking has received extensive news coverage recently. Many consider shale oil / gas with the associated horizontal drilling and fracking as a major development in the oil and gas industry in recent years. Others consider fracking proponents as the public enemy number one. After a brief technical introduction to hydraulic fracturing, I will attempt to give a balanced view of its benefits and the potential challenges. Then, I will highlight major resource opportunities associated with shale oil and gas in general and the California Monterrey shale in particular. I will also discuss some of the real and perceived potential environmental concerns such as contamination of the water column, man-made earthquakes, air pollution and water management. Furthermore, I will discuss the need for new technology development to make the wide spread exploitation of Monterey shale a reality. Finally, I will highlight a recent report (http://gen.usc.edu/news/monterey-shale.htm) on "The Monterey Shale & California's Economic Future"

Beyond purely technical and business factors, successful oil and gas development depends upon a receptive and effective regulatory and governmental policy environment. Establishing this favorable environment increasingly depends upon building public awareness and acceptance. Large-scale shale resource development has raised the importance of industry communications and public understanding of the balance of economic opportunity and operational risks. Enabled by new media and social technologies, the communication process for the industry has become much more complex and dynamic. The diversity of political viewpoints and the perceptions / realities of societal risk are impacting the regulatory process. In this context, Induced Seismicity adds to the complexity of the public debate, and perhaps nowhere more than the emerging opportunity for the development of the Monterey Shale in California. We will discuss the communication and public outreach program developed as an integral component of USC Induced Seismicity Consortium."