Induced Seismicity Consortium (ISC)

A Proposal

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Executive Summary

This proposal addresses a very critical and under-developed aspect of environmental safety associated with hydraulic fracturing operations waste water injection and disposal wells, geothermal resource development, and EOR/CO2 sequestration. The proposed collaborative effort will uniquely integrate efforts of scientists from the Southern California Earthquake Center (SCEC), the Department of Civil and Environmental Engineering (CEE), and the Petroleum Engineering Program of the University of Southern California with industry partners. The consortium will support two key integrated programs: one directed at advancing the the geosciences and engineering technologies to predict subsurface and surface impacts from fracturing and injection processes and one directed a communicating and informing effectively the regulatory and public educational processes regarding such operations. The governance of the consortium’s program and processes will be the responsibility of two corresponding committees. The Strategic Advisory Group will oversee the overall program direction, objectives, and deliverables. It will have specific responsibility for integrating the results of the technical program into an effective external communication process for government and regulatory agencies, consortium members, and a broad array of public and external organizations. The Technical Advisory Group will have the primary responsibility for directing the scientific and engineering investigations of the program, including setting research and development priorities and resources, monitoring technical progress, and assessing deliverables. The Strategic Advisory Board (SAB) is designed to have a representative from each funding member of the consortium, augmented with additional selected members representing government and regulatory agencies and non-governmental organizations. The Technical Advisory Board (TAB) is designed to have a representative from each funding member. Faculty members from USC will provide coordination for SAB and TAB see the management structure in section C-1

The synthesis of capabilities of petroleum engineering, earthquake seismology, and earthquake engineering is intended to produce modeling and data analysis capabilities for predicting seismic impacts associated with hydraulic fracturing, waste water injection or similar operations. Current efforts to interpret micro seismic activity have focused on estimating the stimulated volume and direction of fractured intervals. Our study is aimed at predicting any side effects that multi-stage fracturing or other fluid injection operations may have on the local stress field and fault system, including induced seismicity in natural fault systems, and potential reductions in structural integrity of wells and surface facilities. We will build on our experience from related work in areas such as characterizing fracture network using soft computing and
shear waves, monitoring reservoirs through integrated active and passive seismic data, use of fractals for distinguishing between induced and triggered seismicity, use of fuzzy logic and tomography to create P wave and S wave velocity fields and their changes with time, among other novel approaches. The study will provide a sound scientific and engineering foundation for application to permitting, monitoring, and regulatory processes. The consortium will attempt to address many problem areas as identified by the NRC Committee and through HF-IS workshop interactions including quantification of the risks for surface disruption under different geologic settings, reservoir properties and waste water injection/hydrofracking procedures, addressing the issues associated with waste water disposal that may create induced seismicity, studying different operational procedures in the creation of MEQ events to minimize the need to re-fracture treatments while maintaining efficiency, problems specific to CO2 sequestration, and providing a science-based approach, guidelines and conditions as to where strict regulations are needed.

The proposed work will be based upon a combination of tectonic modeling, scientific analysis, and the interpretation of seismic, geology, production, petrophysical and other usable data. Such a comprehensive study is necessary to quantify the risks associated with hydraulic fracturing and other operations which may cause induced seismicity and the conditions under which they can trigger large damaging earthquakes. The analysis in this project will alleviate public concerns of the likelihood of triggered seismicity and will pave the way to improve fluid injection schemes and their proper monitoring with the ultimate goal of increasing operational safety and efficiency, as well as elevating awareness among the scientific community as well as the general public about the real concerns surrounding induced seismicity. The Consortium will also bring together considerable experience and expertise in the development and communication of research results to government organizations, media, and the public.

**A. TECHNICAL MERIT AND VALUE TO PROGRAM**

**A.1. Proposed Technology/Methodology**

**A.1.1. Statement and Significance of Problem**

A National Research Council report released on June 15, 2012 brought up several important facts on induced seismicity. It concluded that “To better understand, limit, and respond to induced seismic events, work is needed to build robust prediction models, to assess potential hazards, and to help relevant agencies coordinate to address them.”. Waste water associated with drilling, EOR, CO2 capture and storage (CCS) and hydraulic fracturing are among the important factors for induced seismicity. This project is designed in part to carry out many of
the recommendations of the NRC committee on induced seismicity. An in depth understanding of potential seismicity induced by fluid injection and withdrawal activities in relation to the factors effecting the initiation, location, magnitude and mechanisms associated with induced seismicity is essential. A proper understanding of the commonalities and the differences between the mechanics of different human interventions including those between EOR techniques, geothermal developments, unconventional, waste water injection, etc is also necessary particularly where public concerns need to be allayed. As seen in figure 1, while the effects of energy related technologies on possible seismicity in North America seems limited, public perceptions can only be assuaged by the use of research tools to obtain an improved understanding of the underlying science and providing that science out to the concerned parties in easy understandable formats. All of these issues form the core of the challenges that will be taken up by the proposed induced seismicity consortium. The aim is to bring together partners from the industry, researchers from the academia as well as the regulators to formulate strategies and develop technologies that can help secure the future of many of these energy technologies which are vital for future energy security of this country.

Looking at specific energy technologies and related issues in te spotlight, multi-stage fracturing of shale gas and shale oil wells uses several million gallons of frac fluid. Depending on the geomechanical properties of the host rock, the subsurface structure, and the presence and orientation of faults, pumping high volumes of fluid at high rates may disturb the stress field by increasing the pore pressure and create side effects of concern to the local communities. One concern is that hydrofracturing operations may trigger damaging earthquakes. Various investigations of the influence of hydrofracturing on existing faults within the formation, have led to two main points of view. The first argues for a strong correlation between hydrofracturing and the triggering of tectonic earthquakes as would occur if the area of injection was at or near a state of critical stress. The second argues that this apparent correlation is based on poor reasoning, unproven theories, and insufficient evidence (this just means that the relationships are poorly understood or too complex to understand without further study).
The generation of micro earthquakes during hydrofracturing or waste water injection, and normal and sustained production or disposal of produced water is well-documented. There is also some evidence for the triggering of small tectonic earthquakes. The magnitude 2.8 events on June 2, 2009 at Cleburne, Texas (Northrup, 2010) are believed to have been caused by water disposal and the magnitude 4.7 earthquake on February 27, 2011 at Arkansas is suspected (but not confirmed) to have been caused by horizontal hydrofracturing (Thompson, 2011). While both tensile and shear fractures can be nucleated by fluid injection, the radiation from tensile fractures is generally too high a frequency to be detected by seismic instrumentation. The vast majority of microearthquakes that are detected by seismic monitoring are the result of shear fracturing. These small shear events are nucleated by the injection (or leakage) of pressurized fluids into existing fractures. The resultant reduction in normal stress across the fracture surfaces reduces the effective friction and allows a stick-slip shear event. The chief concern is that this process might trigger a large damaging tectonic earthquake.

We hypothesize (yet to be substantiated) that the probability of triggering a damaging earthquake in a given location depends on its geology and subsurface properties. Other factors suspected of influencing induced seismicity include stress field, formation pressure, temperature, depth, fluid saturation, formation thickness, local faulting/ fracture network, rock type, injection rates and volumes injected. Areas with younger sediments and less consolidated rocks with active faults blocks are more likely to generate large triggered events. In general, areas which are already susceptible to earthquakes will naturally be more sensitive to external stimuli (drilling, hydrofracking, production, etc.). Other regions with different geological characteristics, such as hard bedrock and within the continental interior, can withstand such activities without a substantial risk of a large triggered event. The Rocky Mountain Arsenal is such a location, and is subject to significant risk. For example in Wilmington, California, the formation of new faults in the bedrock was suspected to be caused by subsidence, resulting in moderate size earthquakes (magnitude 2-4). In most cases, however, a large stressed fault, which already exists in the formation, will be the main source of a large damaging seismic events associated with triggered seismicity. In the absence of large faults and tectonic stress, fluid injection activities are not likely to induce catastrophic earthquakes. This is because of the limited energy input by the same compared to that released by large-scale tectonics events (Thompson, 2011). The rupture surface of the Wilmington events was not large enough to produce a M3 EQ. This example however needs further study.
There is a need to scientifically study the conditions under which hydrofracturing or other injection activities can or cannot trigger large damaging earthquakes. The arguments that frac jobs do not produce large earthquakes are often cited as:

- The type of stress release in hydrofracturing and waster water injection is more of a tensile based which is different from the shear stress which makes the rocks to move along the fault. Also, the energy level which is released is large enough to be recorded, but too low to directly create major seismic events.
- The source volume defined by the migration distance of the fluid in the hydrofracturing and fluid injection r withdrawal process is too small to generate a large damaging event
- When compared to the conventional injection wells, hydrofracturing inserts a much smaller volume of water into the ground
- The duration of a fracking process is significantly shorter than that of a traditional (non-pressured) injection (Thompson, 2011)

As stated by Peng et al. (2010), hydrofracking moment is much lower than earthquake events (Figure 2). In this figure, dashed horizontal lines connect related geodetic and seismic data and solid horizontal lines highlight the gap between seismic and geodetic durations. Nonetheless, there are some concerns backed by observational evidence that triggered seismicity should be taken seriously. Some people believe there is always the possibility that injection will reduce the normal stress across a large critically stressed fault to trigger a large damaging earthquake. However, most oil operations try to balance fluids in with fluids out, thus reducing the potential for major pressure im-balance, thus reducing the chance of large events. Also frac jobs usually inject small total volumes of fluids compared to the volume of rock that was injected into. Low permeability rocks allow the frac fluids to penetrate farther from the well bore.

Before national concerns result in total shut down of hundreds of planned wells, there is a need to undertake a scientific investigation using rigorous modeling and data analysis to quantitatively assess the probability of such a scenario. We propose that this the new consortium will study the same using unique capabilities at our earthquake study center, as
well as our reservoir monitoring and civil and environmental engineering teams to address public concerns. The studies will be based upon a combination of tectonic modeling, geological and geophysical mapping, scientific analysis, and the interpretation of seismic and other necessary field data. Such a comprehensive framework for study is necessary to quantify all the potential risks associated with hydraulic fracturing and the conditions under which it can trigger large damaging earthquakes. Not only can such analysis alleviate public concerns of the likelihood of triggered seismicity, it may also pave the way to improve hydrofracking and other fluid injection procedures and more importantly, their proper monitoring. This may result in model-based guidelines for the pressure level, frequency, and duration of fluid injection that is tolerable for a given number and separation of wells in a given geologic regime, characterized by the nearby faults and natural tectonic activity.

A.1.2. Background and Existing Technologies/Methodologies

Production of unconventional resources from tight and low permeability reservoir rocks is achieved by hydraulic stimulation through borehole injection to create permeable zones, a process that involves fracture initiation and/or the opening of discontinuities such as faults and joints due to pore-pressure and in-situ stress perturbations. Hydraulic fracturing performance can be evaluated by measuring fracture lateral length and orientation, treatment size, number of injection stages, perforation clusters, and diversion techniques and/or openhole packer completion system (Mayerhofer et al., 2010). Hydraulic stimulation of rock is typically accompanied by multiple microseismic events, which are believed to be associated with rock failure in shear modes [Peasron, 1981]. While the true nature and source of such events remains to be fully understood, many mechanisms for triggering micro-earthquake (MEQ) events have been proposed in the literature. Among these, the pore-pressure relaxation is common. The pore-pressure relaxation hypothesis postulates that a rise in fluid pressure in a reservoir increases the pressure in the connected pore space of the rock, thereby increasing the pore-pressure and decreasing the effective normal compressional stress on rock surfaces. In critical locations which are loaded in shear, the fall in the compressional stress can result in sliding.

The Frenkel-Biot equations for acoustics of poroelastic systems [Biot, 1962] in a homogeneous isotropic saturated poroelastic medium, identifies three waves (P, S and a dissipative slow wave named Frankel-Biot). Field evidence suggests that evolution of MEQ events is a relatively slow process that is likely to be associated, at least in part, with the Frankel-Biot wave. The pore-pressure variation in the slow wave can be described by a simple
diffusion equation for a homogeneous isotropic porous medium. Recent studies have proposed a similar diffusion equation for describing the spatiotemporal evolution of pore-pressure relaxation in heterogeneous anisotropic porous media. In the pore-pressure relaxation theory, rock failure occurs at locations in the reservoir where the pore-pressure exceeds rock criticality. To implement this failure criterion with the pore-pressure relaxation assumption, the diffusive pore-pressure equation is solved first. This forward model relates rock hydraulic conductivity distribution to pore-pressure distribution, which is directly related to the rock failure mechanism and the distribution of microseismic events (data).

The spatiotemporal distribution of MEQ events has been observed to carry signatures of a diffusion-like process (including a triggering front at the front and back front of the seismic waves) consistent with the diffusive nature of pore-pressure distribution. Other observations supporting the above hypothesis are the ellipsoid-shaped seismicity clouds after normalization of the event coordinates by their occurrence time and the spatial density of MEQ events. The microseismic signals contain information about the source locations and have been used to understand the hydraulic fracturing process. Detection and interpretation of microseismic events is useful for estimating the reservoir permeability, the stimulated zone and fracture growth, as well as the geometry of the geological structures and the in-situ stress state.

Various methods have been suggested to monitor hydraulic fracturing and assess hydrofracturing performance. One approach has been to study the microseismic events that are produced by the sudden opening of old fractures and growth of new ones caused by the fluid injection. The elastic waves generated by such microseismic events can be used to locate the fractures and assess their sizes. The attributes of this microseismic activity can be used to monitor the nature and extent of fracture propagation (Taleghani et al., 2011). Furthermore, fracture orientations deduced from microseismic event locations and signal characteristics can

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**Figure 3.** MEQ characterization and observation of possible fault activation with low b-values (Maxwell et al., 2011)
then be compared to the pumping data, reservoir structure and geomechanical state to further investigate the geometry of the fracture surface. Our proposed study examines the larger scale impact of a single well and, particularly, of a group of wells fractured in close proximity (Taleghani et al., 2011).

Seismic monitoring is a common practice applicable in most unconventional reservoirs that utilize hydrofracturing. The seismic data is analyzed to monitor fracture growth and propagation in an area under the study. Microearthquake (MEQ) as well as conventional seismic studies can give an accurate estimate of the fracture properties in reservoir. Most of these studies are done by analyzing microseismic characterizations such as spatial locations, b-values, Coda Q, and Vp/Vs. Figure 3 shows the use of seismic moment density and b-value for MEQ characterization. The key question is whether the earthquake activity stimulated by hydraulic fracturing is likely to trigger slip on a large critically loaded fault. This is actually two questions: 1) is there significant tectonic stress in the area, and 2) is there a large capable fault in the vicinity? If the energy released by induced seismicity, comes mainly from the injection process itself this might be taken as evidence that the tectonic stress level is low. If, on the other hand, the released energy is independent of the fracking energy this may be taken as evidence that the tectonic stress is high and large damaging events are possible.

Recent advances also include integrated approaches towards hydraulic fracture characterization using seismic derived properties in addition to observed micro-seismicity. Figure 4 shows the use of faults maps, Poisson’s ratio and ISIP data to validate possible fault activation as a result of fracturing process. By a through investigation of MEQ events suspected to be generated by hydraulic fracturing, the real cause and effect of oil field operations versus the measured seismic events can be defined. One approach to quantify such relationship is through use of artificial neural networks (ANN). This approach has been applied both for the analysis of natural earthquakes (Aminzadeh et al. 1994) and injection caused
seismicity (Aminzadeh et al. 2012). In both cases, we extract the key “seismic attributes” from the MEQ data and combine these through a neural network to substantiate certain hypotheses.

**B. TECHNICAL APPROACH**

**B.1 Detailed Work Plan (Statement of Work)**

**B.1.1 Objectives**

This consortium aims to address critical aspects of environmental safety associated with hydraulic fracturing. The proposed research under this consortium intends to produce modeling and data analysis capabilities for predicting induced seismicity associated with hydraulic fracturing. Studies will be aimed at predicting any side effects that multi-stage fracturing jobs may have on the local stress field and fault system. The ultimate goal is to investigate and predict the potential of triggering large and damaging tectonic earthquakes as well as studying possibility of failure in a hydrofracturing, waste water injection or CO₂ sequestration site. Also, this research may result in model-based guidelines for the pressure level, frequency, and duration of hydrofracking or other injection schemes that is tolerable for a given number and separation of wells in a given geologic regime, characterized by the nearby faults and natural tectonic activity.

**B.1.2 Scope**

The scope includes development of necessary methodologies and models to understand the nature of significant seismic events that are a direct consequence of the hydraulic fracturing process. The goal is to determine the probability of triggering a large tectonic event in different geologic settings and to better characterize the effects of different fluid injection schemes in the subsurface. The first step in this effort would be focusing on and analyzing microseismic attributes such as spatial locations, b-values, Coda Q, and Vp/Vs. We will begin by calculating the hypocentral locations of events from the first arrival times for both P and S waves. We will then carry out fractal analysis, fuzzy clustering, tomographic inversion, stress analysis, and shear wave splitting analysis to characterize the structure and evolution of the fracture network.

The next step will be employing Artificial Neural Networks (ANN) in an effort to find the relationship between microearthquakes (MEQ) suspected to be generated by hydraulic fracturing and the measured seismic events. Based upon former experiences, an ANN model to correlate MEQ events and microseismic attributes would work quite well.

The primary contribution of the SCEC seismologists to this consortium will be to develop a method that uses natural and induced seismicity to map the fracture network in the reservoir. Since earthquakes almost always occur on the preexisting network of faults and fractures, this
structure is revealed by the spatial pattern of hypocenters. Additional constraints on the structure can be obtained from the magnitudes of individual events since the larger events occur on larger faults. The ultimate measurement in this context is the focal mechanisms or moment tensors of the events. This has generally not been possible for small events since it is difficult to identify the first P let alone measure its polarity. However, recent progress has been made in using both P and S wave amplitudes to find focal mechanisms for small earthquakes (Hardebeck and Shearer, 2002) and are just recently being applied to microseismic monitoring efforts (Baig and Urbancic, 2010). Moment tensors can be further represented in terms of source type (Hudson et al., 1989), a classification scheme that includes shear slip (double couple), dipole, compensated linear vector dipole and volumetric sources. But these classification schemes are highly dependent upon the geometry of the recording array that satisfies geometrical requirements for azimuthal coverage of the source region (Eaton and Forouhideh, 2011). However, the determination of moment tensors can potentially provide useful insights into rupture processes. Shear wave splitting can provide an addition constraint by identifying any prominent orientation (fabric) of the faults and fractures over a broad depth range. Our ultimate goal is to combine this seismic imaging with geological structural analysis to assess the probability that the reservoir contains a large critically loaded fault that might be triggered by the injection processes.

We can also bring our expertise in earthquake mechanics to bear on this problem. Earthquake seismology studies suggest that rock-deformation processes occur across a broad spectrum of time scales and frequency, wherein earthquakes merely represent a high-frequency endmember (e.g., Beroza and Ide, 2011). We postulate that rock deformation processes associated with fracking obey scaling laws that are similar to earthquakes. For example, the fractal dimension of the active fracture network is related to the slope (b-value) of the Gutenberg-Richter frequency magnitude relation. While the fractal dimension of tectonic seismicity is near D=2 and the b-value is near 1 (Robertson et al., 1995), the fractal dimension of induced seismicity in The Geysers geothermal reservoir is significantly higher (D=2.6) as is the b-value (b=1.3) (Tafti et al., 2012). The simple explanation is that tectonic strain only utilizes near vertical faults, which have a lower normal stress. The reduction in normal stress associated with fluid injection also activates more horizontal faults, which leads to the higher values for D and b. We will explore whether this difference in activation has implications for triggering of large faults.

Another example of an interesting mechanical issue is whether the relatively shallow depth of the hydrofracturing limits the size of any triggered earthquake. It is well known that most
large earthquakes nucleate at the base of the seismogenic zone (10-15 km deep) and propagate toward the surface. The shallow nucleation of large events is rare. Since the magnitude of all but the largest earthquake is proportional to the logarithm of the radius of its fault zone, and since earthquakes almost always propagate from their hypocenters toward the surface, the magnitude of the largest triggered earthquake should be proportional to the logarithm of the depth of the hydrofracturing or fluid injection. We will use high-quality seismic catalogs to establish this relationship and, more importantly, examine the few exceptions to this rule to see if we can understand the difference. This analysis should help identify reservoirs which pose a special threat of nucleating a large earthquake from a shallow hypocenter.

As it was stressed out before, implementing hydrofracturing in a site is always associated with certain amount of energy releases as well as MEQs which can be recorded and analyzed. The same holds true for other injection schemes such as EOR techniques and CO$_2$ sequestration, etc. One important problem that will be addressed together with the other proposed efforts is the quantification of impacts and how to control hazards rooted from the induced seismicity. In order to better understand this issue we need to define seismic risk components. Seismic risk is basically a combination of two different elements: seismic hazard and exposure. Seismic hazard is defined by the probability of ground motion and exposure is the duration of time an object is exposed to the earthquake. Exposure itself is categorized into three sub-categories: people, buildings, and infrastructures. Seismic hazard is not alterable due to the not perfectly understandable fact of natural earthquake happening. This hazard, thus, can only be quantified in an effort to help scientists provide practical guidelines on how to reduce the exposure time and also how to do risk management. On the other hand, induced seismicity has a very predictable hazard which is borrowed from the condition under which it is generated in a reservoir. As a result, when dealing with induced seismicity it is reasonable to put efforts on just controlling the hazard and not to take the exposure into consideration since exposure does not play a significant role in this case (Bommer et al. 2006). Figure 5 shows a typical hazard analysis scheme associated with induced seismicity for a single well. More complex schemes with fuzzy inference schemes may be necessary to incorporate reservoir wide or more regional risk mitigation schemes.
One critical aspect in designing a control system is to pay enough attention to the issue of human discomfort. When the injection process is in progress there must be some assurance that induced seismicity intensity does not exceed a threshold of human feeling. Otherwise, once the induced seismicity is great enough to annoy humans living nearby the site, there will be complaints and sometimes protests against the work of injection (Bommer et al. 2006).

In addition we will develop methodologies to generate hazard maps identifying areas that are most susceptible to potential risks from sustained hydrofracking or other injection programs related to energy developments.

B.1.3 Tasks to be performed under selected consortium projects

Task 1.0 Project Management Plan

We shall develop a Project Management Plan consisting of a work breakdown structure and supporting narrative that concisely addresses the overall project as set forth in the agreement. We shall provide a concise summary of the objectives and approach for each Task and, where appropriate, for each subtask. We shall provide schedules and planned expenditures for each Task including any necessary charts and tables, and all major milestones and decision points.
We shall identify key milestones that need to be met prior to project proceeding to the next phase. This report is to be submitted within thirty (30) days of the Award. The partner entity shall have twenty (20) calendar days from receipt of the Project Management Plan to review and provide comments. Within fifteen (15) calendar days after receipt of the said comments, we shall submit a final Project Management Plan to the partner entity for review and approval.

**Task 2.0 Technology Status Assessment**

We shall perform a Technology Status Assessment and submit a summary report describing the state-of-the-art of the proposed technology. The report shall include both positive and negative aspects of each existing technology. The report is to be submitted within thirty (30) days of the Project Kick-off. The report shall contain the following: (1) Current State of Technology (Summary of Background of Industry/Sector; Technologies/Tools/Processes/Strategies Being Used; Benefits and Inadequacies of Current Technology/Methodologies); (2) Development Strategies (Why New Technology and Research is Required; Problems to Address in this Research Project); (3) Future (What Barriers will the Research Overcome and the Impact on the U.S. Domestic Gas Supply Industry, including environmental impacts; Deliverables – Tools, Methods, Instrumentation, Products, etc.) and (4) References.

**Task 3.0 Technology Transfer**

We will work with partner entity throughout the project to develop and implement an effective overall Technology Transfer program. Technology Transfer activities will consist of both project and program level activities. The total cost of the project is the value of funds to be provided by the partner entity plus the value of the project cost share if any. We shall nominate work/activities for 1.5% of the total cost for project level technology transfer activities. This work/activities may typically include writing technical papers and, as appropriate, participation in agreed to conferences and workshops. Project level Technology Transfer Plans will be submitted to the partner entity within thirty (30) calendar days of Project kick-off. Technology transfer activities will also be detailed in the Project Management Plan. We will report the cost associated with project level technology transfer activities on each monthly report. We shall provide information requested by the partner entity to support any quantitative estimation of program benefits that may be required by any third party.
Task 4.0 Other Reports and Special Items
Upon subcontract execution, we should coordinate with the partner entity to plan and schedule the Project Kick-off Meeting(s). Monthly and/or quarterly reports will be provided as per mutual agreement. Baseline cost estimates for the monthly reports will be submitted by task. A monthly report containing the estimated or actual expenditures by month will be provided. Progress on the task deliverables will be reported in the monthly reports. Additional or supplemental information will also be provided as they become available. USC will provide for project presentations or project meetings as required by the partner entity. Scheduled meetings at locations of choice may be planned for in consultation with the partner entity. A final project presentation as well as a comprehensive project report will also be provided by USC following the Project completion.

Task 5.0 Characterizing Fracture Network Using Microseismic Data
This task will look towards identifying fracture network properties by using microseismic data obtained from seismic receivers in offset wellbores. In this manner, we use a procedure which is both comprehensive and flexible compared to other technologies. In this method, a series of steps must be taken in order to calculate and define seismic attributes. Thereafter, these attributes can be used to train the ANN models and smarter (hybrid) soft-computing schemes as necessary.

5.1 Picking P-phase and S-wave Arrivals
Compressional and shear waves are picked to generate event locations using tomographic inversion. The detection of phase arrivals is of vital importance in obtaining accurate time differentials to be used for tomographic inversion schemes to obtain estimates of velocity and microseismic hypocentral locations. Improved accuracy in the arrival times should lead to better inversion results. Traditionally, this task has been done by human analyst in a visual way. Visual analysis is a time consuming and subjective task that cannot manage the huge volume of digital and real time microseismic data recorded today by different arrays of receivers. Even smart autopickers have inherent limitations which make human intervention necessary. Lack of fast, robust and truly automated picking algorithms is a major deterrent towards real-time or near-real time MEQ monitoring. Moreover, highly accurate picks become important as situations where the background velocity models are not well defined or where we have limited amount of phase arrival data available for inversion leading to associated
calculation errors. In this study, we will use first arrival picking method based on an ANN based automatic detection approach (figure 6).

Over the last two decades, numerous algorithms have been developed for automatic detection and picking of first arrivals based on energy analysis, polarization analysis, artificial neural networks, maximum likelihood methods, fuzzy logic theory, autoregressive techniques, higher order statistics, or the wavelet transform (Leonard, 2000; Dai and MacBeth, 1995, 1997; Zhao and Takano, 1999; Al-Ghamdi, 2007; Sabbione, 2010; McCormack et al., 1993; Veezhinathan et al., 1993; Aminzadeh et al., 1994, 2011). Location and magnitude of the events can be determined using inversion schemes such as pseudo-bending, ray-tracing algorithms and they can be further characterized based on integration of different methods namely fuzzy clustering, fractal analysis, and b-value analysis.

5.2 Estimation of Fracture Orientation and Density
One of the most effective ways to detect the fracture orientation and density of subsurface is shear wave splitting of microseismic events. When shear wave hits the fracture induced anisotropic medium, it splits into two components which show up as fast and slow arrivals on the seismogram. Polarization angle of the fast component which is parallel to the fracture indicates the fracture orientation once rotated to get the maximum energy on one of the components and the time delays observed between the slow and fast shear waves give information about the density of the fracture.

Shear wave splitting has been successfully used to identify the orientation of primary and secondary stress aligned fractures. Polar histograms can be used to indicate the dominant direction of fast shear wave motion at each receiver of the array. Equal area projection plots of
normalized time delays can also be used to display the crack density. Fracture properties calculated based on this technique (possibly with the aid of the conventional or three component reflection seismic data) can be an important tool for fracture mapping within our study area. Figure 7 illustrates the results of this analysis done by Elkibbi, (2005) and Tafti, et al. (2012).

Conventional seismic data can also be used as an additional tool to obtain usable fracture properties. AVAz analysis on pre-stack 3D seismic data can provide valuable information regarding fracture orientations and possible insight into anisotropic parameters which can be used to improve upon the interpretations made through microseismic data analysis. Pre-stack attribute studies can also shed some light on the same. By varying the offset and the azimuth, different azimuth amplitudes and frequencies can be calculated and their spatial distribution can be used to extract fracture density and orientation information. Over the years, many workflows have been developed to conduct AVAz studies (Gray, et al. (2002); Sun, et al. (2012); etc.) and can be used as another tool to characterize the “open fluid filled” fractures and local stress mapping.

5.3 Identification of Fracture Location and Size
During the hydrofracturing or other injection operations, fractures with different sizes and at different locations start to build up. Fracture propagation is associated with generation of microseismic events, which can be detected via application of downhole or surface array of three component receivers. The number and reliability of events reported in microseismic monitoring either from surface or downhole monitoring varies dramatically depending on the first arrival picking criteria that is used. The detection of phase arrivals is of vital

Figure 7. (a) fracture density result from shear wave splitting (Elkibbi, 2005), (b) VP, (c) VP/VS (d) Poisson’s ratio, (e) Extensional stress Tafti, et al., 2012
importance in obtaining accurate time differentials to be used for tomographic inversion schemes to obtain estimates of velocity and MEQ hypocentral locations and has been discussed in section 5.1.

Relating cluster of events to each injection well or stimulation stage is difficult while monitoring the microseismicity cloud around wells or within hydraulic fracturing stages. Hence, to find the movement of microseismicity cloud or possible fracture network propagation with time, fuzzy logic can be utilized as a powerful tool. The fuzzy clustering algorithm involves dividing the event into zones based on the location of treatment wells and hydrofracturing stage or injection locations where sufficient aggregation of seismicity is present. A radial distance is selected for clustering in order to understand how the cluster centers move with time. The windowed time for hydrofracturing depends on time required for each simulation stage. Similarly, the time required during fluid injection programs relates to the volume of fluids in question as well as the injection scheme being followed. Interpreting the movement of these cluster centers can be useful in locating the front of fracture network and also allowing more accurate interpretation of fracture patterns and broader understanding of the underlying physics.

In the next stage, self-similarity of the fracture patterns using fractal geometry and the possible correlation between microseismic events and the fracture network characterization can be investigated. Then to gain a better understanding of the fracture network and the reservoir heterogeneity, the fractal concept of the hypocentral distribution of microseismic events can be analyzed. If the fractal network is self-similar (scale independent) then its structure, mechanical, and transport properties are best described using fractal geometry. Microseismic events can be characterized by the fractal dimensions of hypocenters to assure that there are enough sampling points to measure the true dimension of the underlying fracture network, the observed fractal dimensions should be plotted as a function of the density of the events. Figure 8 demonstrates primary clustering for fractal analysis in a specific area of interest.

![Figure 8. Primary Clustering for fractal analysis (Tafti, et al., 2012)]
After fuzzy clustering, b-value analysis is the next step to go through. The microseismic events can be characterized by the b-value of their frequency-magnitude distribution. The Gutenberg-Richter equation is used in this regard. In recent years b-value analysis has found its application in monitoring and characterizing the fracturing process. Using this technique we will be able to find thresholds to differentiate “Induced” and “Triggered” seismicity. Here, spatial distribution and frequency – magnitude distribution of microseismicity are calculated to obtain information about fracture network.

Improved modeling workflows for hydraulic fractures and stress modeling using available and novel reservoir simulation modeling techniques can also provide valuable information on possible reactivations and interactions with existing natural fracture swarms. Williams-Stroud et al., 2012 showed how the response of hydraulic fracturing on natural fractures can be accessed through surface microseismic arrays. The distinction is critical in understanding the effects of the injection schemes on the reservoir and to prevent “unwarranted” scenarios using pre-emptive actions as necessary. Figure 9 shows a comparison of the actual event clouds and the DFN modeling results with the interpreted strikes indicative of failure mechanisms. Improved modeling techniques can therefore allow us to better understand the rock behavior and provide a more holistic and scientifically sound view of the real effects due to frac or other injection schemes.

Figure 9. MEQ events from simulation model compared with modeled reservoir fractures with the strikes compared

Another important issue to be studied in shale reservoirs is the impact of fractures (natural or induced) on seismic velocities and elastic rock properties (Tafti et al., 2012). Analyzing the related anomalies can be helpful in mapping the fracture density through the stimulated
volume. Typically, highly fractured regions demonstrate lower Vp and Vs values, whereas high values of Vp and Vs can be representative of un-fractured regions (Berge et al., 2001). Figure 10 pictures the result of the analysis carried out by Tafti et al. (2012), new methods were used to invert for Vp, Vs, Vp/Vs, Poisson’s ratio, Extensional stress, and Hydrostatic stress.

![Figure 10](image)

**Figure 10.** (a) $V_p$, (b) $V_s$, (c) $V_p/V_s$, (d) Poisson’s ratio, (e) Extensional stress, (f) Hydrostatic stress (Tafti, et al., 2012)

Similar approach including use of advanced ANN based MEQ event picking and co-kriging techniques in geothermal reservoir settings aimed at integrating seismic and microseismic data to characterize possible fracture swarms and fluid flow pathways are shared in figure 11.
In addition, we would build on the work by Tafti et al. (2012) to exploit the fractal dimension calculated from the MEQ data to predict the induced versus triggered nature of the seismic events. The idea here is very simple. Triggered tectonic earthquakes tend to occur preferentially on vertical faults where the lower normal stress results in a lower effective friction. In consequence the fractal dimension is near 2 and the related Gutenberg-Richter b-value is near 1 (Robertson et al., 1995). Induced microearthquakes tend to exploit the natural fracture network. They have a fractal dimension larger than 2 and a b-value greater than 1. By monitoring the fractal dimension and b-value of the seismicity associated with the fracking, one can determine if the events are triggered and a large damaging event is possible, or if they are induced and such a large event is highly unlikely. Real time monitoring of b-value and possibly fractal dimensions can be possible based on some recent developments involving time lapse of a few minutes to assure adequate data for necessary calculations. Figure 12 shows how windowed b value calculations can be used to identify possible faulting related MEQ initiation during a hydrofracturing operation (Kratz, et al., 2012).
During the hydrofracuring operation fractures with different size and location start to build up. Fracture propagation is associated with generation of microseismic events, which can be detected via application of downhole or surface array of three component receivers. The number and reliability of events reported in microseismic monitoring either from surface or downhole monitoring varied dramatically depending on the first arrival picking criteria that is used.

**Deliverables of Task 5.0**

1) Development of theoretically sound and practical seismic methodologies for fracture characterization from microseismic measurements

2) Generation of new algorithms for identification of fracture geometric properties such as location, size, orientation and density.

**Task 6.0 Developing ANN Model to Correlate MEQ Events and Microseismic Attributes**

Through investigation of MEQ events suspected to be generated by hydraulic fracturing, the real cause and effect of oil field operations versus the measured seismic events can be defined. One approach to quantify such relationship is through use of ANN. This approach has been applied both for the analysis of natural earthquakes and injection caused seismicity. In both cases, the idea is to extract the key “seismic attributes” from the MEQ data and combine these through a neural network to substantiate certain hypotheses.
6.1 Developing Adaptive Neural Nets

Building on the previous experience we propose to develop a model based on ANN to correlate MEQ events and microseismic attributes. After training with available data, the model can be used as a tool for prediction of possible earthquakes using related hydrofracturing parameters.

While performing fluid injection, there are many operational factors involved in occurrence of an earthquake each with a specific degree of contribution. Out of which injection depth, fluid injection volume and flow rate stand out in importance. In this study, the degree of each factor will be quantified to develop a model to predict seismic activity and subsequent earthquake. For this purpose, data from various hydrofracturing operations will be gathered, analyzed, and used as an input to Adaptive Neural Network (ANN) model. Model will be trained to be able to anticipate future occurrence of earthquakes. Input data would include b-value, Coda Q, Vp/Vs, etc. The ANN is trained to approximate the values of D (t+τ) using microseismic data in the interval (t, t-te). Then, using the synthesized ANN and seismic data at time T>t, we produce the estimate of the value D (T+τ). If the estimate is larger than a threshold, it is assumed to be a precursor for an earthquake for the time T+τ.

6.2 Developing Reverse Adaptive Neural Nets

In reverse experiments, the adaptive neural net is trained to predict values of the danger function calculated for different scenarios. Inverse modeling and sensitivity analysis are developed to calculate fracture propagation with hydraulic fracture properties. Frequency – magnitude distribution is correlated with hydraulic fracture parameters using ANN in order to get a predictive tool for simulating earthquake event trigger and development based on hydraulic fracture parameters.

Deliverables of Task 6.0

1) Development of a new ANN approach for correlating fracture distribution with MEQ events and microseismic attributes

Task 7.0 Developing a Hierarchical Probabilistic Model for Operational Parameters

Given an estimate of the fracture network in the subsurface, our models will ascertain whether a particular injection strategy will cause failure at a particular site. A more accurate statement would refer to the probability of failure occurring at a given site,

Figure 13. Using hierarchical probabilistic model to predict failure
reflecting on the observation that this inference is predicated on a particular (simplified) model and a finite set of data, introducing uncertainty in the calibration and ensuing prediction. The prediction process is highlighted in figure 13. Hazard maps, obtained in this fashion, are themselves a function of the selected model and data, and their sensitivity with respect to additional data and/or model refinement can be used to design data acquisition efforts and model refinement through multi-scale modeling. We thus propose to develop a hierarchical probabilistic model the parameters of which reflect subscale effects, and whose sampling distributions can be accurately estimated from data. Sensitivity of the hazard maps with respect to these parameters will then reflect the value of additional measurements and additional model complexity.

The hazard associated with hydrofracturing can be traced to 1) events taking place along a fault, 2) the propagation of these events in the subsurface, and 3) the interaction of subsequent motion with structures and features either buried or on the ground surface. Uncertainties can be associated with each of these components, resulting from distinct sources of ignorance. Fracture density and orientation, estimated from shear wave splitting, will be characterized probabilistically from microseismic event data. This will be combined with the fuzzy clustering algorithm where some features will be characterized using fuzzy sets while others, will be described using probabilistic models. Specifically, within each fuzzy cluster used for fractal analysis, a probabilistic model will also be deduced from the data using maximum entropy principles (MaxEnt).

The probabilistic evidence of the initial fractures will be propagated through physics-based models whose parameters are treated as random variables thus leading to a predicted probabilistic fracking behavior that depends on both uncertainty in initial hydrofracks and wave propagation in the heterogeneous medium. To describe the uncertainty in the random model we will again use MaxEnt to describe the constraints associated with physics (symmetry, positivity, and upper/lower bounds on effective behavior) and data (in the form of statistical moments) (Das and Ghanem 2009; Arnst and Ghanem, 2008).

**Deliverables of Task 7.0**

1) A hierarchical probabilistic model for the operational parameters which is calibrated based upon the collected seismic

2) Hazards maps will be constructed that reflect the interaction between uncertainties, models, and risk and that provide a visual aid for decision-making.
Task 8.0 Developing a System to Control the Hazard Associated with Induced Seismicity

Designing a real-time data acquisition system would be a beneficial tool to address hazard issues associated with tectonic activities of faults. Here, we are proposing a calibrated control system equipped with powerful ground motion measure instrumentation. When using this technology ground movements caused by induced seismicity can be monitored and managed over the course of time (Bommer et al. 2006). As per Bommer et al. (2006), this system must operate like a traffic light with the ability of determining under what conditions the process of injection can go on, should be stopped, or when there are some adjustments needed in operational parameters (such as the injection rate). In particular, a good design for a system will be functioning continuously without losing time in estimating the hazard, also with employing simplicity to the process of decision making as a whole.

The monitoring system comprises of seismograph network to detect microseismic activity, strong motion accelerographs to provide instrumental verification of the actual peak ground velocity (PGV) levels, and a center to gather the whole data on a real-time basis. This center can be connected to the onsite instruments via communication technologies such as radio telemetry. Also, there are sensors and geophones needed to be installed on site. Employing such a system in a hydrofracturing site will enable us to acquire and analyze data continuously, find relationships between operational parameters (e.g. injection rate and more importantly the injection pressure) and the seismicity level, and finally define regions under which hydrofracturing operation can be done safely. Figure 14 suggests a so called “Traffic Light” system with separated zones of safety.

![Traffic Light system](image)

**Figure 14:** Traffic Light system (Bommer et al. 2006)

In this hazard control system, Green zone is the safe region for the hydrofracturing process and all the elements of system are perfectly in operation. When shifting to the Amber area,
more cautious approach must be taken since the level of seismicity is reaching the thresholds which are sensible by human beings or which are dangerous to structures. And lastly, presence of events in the Red area must be followed by immediate response of the management team because of the high hazard potential of the accompanying seismic activities (Zobak, 2012).

Finally, a guideline can be provided which further defines under what conditions we can name a hydrofracturing process as a “Safe” operation. This guideline could be a reference for future hydrofracturing jobs. The importance of creating an operational guideline is even more important when working in areas with higher degree of tectonic activities. Nonetheless, monitoring of small earthquakes are also important because once felt by people, there can be problems and concerns arising from public about the injection process (Zobak, 2012).

**Deliverables of Task 8.0**

1) A “Traffic Light” system for different operational parameters and related conditions

**B.2 Project Deliverables – Schedule**

Each deliverable as described under the specific tasks envisaged under proposed Induced Seismicity Consortium have been defined as broadly outlined agenda items for the Technical and the Strategic Advisory boards to consider. Depending on the scope of individual projects and the path defined by the boards, the final specifics regarding the deliverables will be decided.

**Year1:**

1. Projects will be identified and depending on the scope and complexity of the projects, workable project management plans will be outlined.
2. Thorough research on current “state of the art” and associated areas of research in other related fields will be identified and possible opportunities for cross-disciplinary technology sharing/ development will be defined. An example could be leveraging MEQ related technologies used in mining industry in the unconventional oil and gas space.
3. Detailed project action plans will be drafted and resource allocation will be completed. These would include necessary cost share (valuable field data and available expertise) from the partners entities along with necessary manpower.
4. Independent work on some of the deliverables will be taken up as deemed necessary (by the TAB).
5. High resolution, robust event detection and inversion algorithms will be developed for practical use.
6. Real time monitoring schemes will be devised for multi-scale operational scenarios by making use of available technological inputs. Additional inputs as required will be identified and work on developing necessary tools to obtain said inputs will be taken up in parallel.
7. Integrated fracture and stress characterization from induced seismicity will be worked on with actual field test cases and techniques developed for the geothermal reservoir settings will be migrated to and applied on unconventional oil and gas settings.

Year 2:
1. Progress on deliverables for the first year will be evaluated and preliminary results will be shared as per the technology transfer protocols to test and validate developed technologies/ strategies and hypothesize some results including preliminary hazard and risk analysis framework and tools with necessary adaptability for future upgrades.
2. Integrated fracture characterization workflows, particularly those involving integration of stress related information with b-value and fractal results will be tested and deployed where applicable. “Best Practices” and “Standardized” procedures including necessary software tools will be developed.

B.4 Recommended Educational Technology Transfer Approach
We will use two main avenues for technology transfer from the proposed project:

1) Professional training: results of ICS will be properly incorporated into both internal educational programs (USC Students) and external educational programs ((oil industry people):
2) Public outreach: educating the general public, and interacting with policy makers, regulators and environmental groups

C. TECHNICAL AND MANAGEMENT CAPABILITIES
C.1 Organizational Capabilities and Experience
The Viterbi School of Engineering and Petroleum Engineering Program at USC have strong world-class research facilities and resources to conduct the proposed research and development activities. USC has several core units and centers that actively work on various
aspects of reservoir engineering and subsurface characterization and monitoring. These facilities, laboratories and centers provide unique opportunities for researchers to coordinate and collaborate, while conducting independent research. Among the existing centers, Southern California Earthquake Center (scec.usc.edu), USC Energy Institute, the Center for Interactive Smart Oilfield Technologies, (cisoft.usc.edu), Global Energy Center (gec.usc.edu), Center for Geothermal Studies (cgs.usc.edu) and Reservoir Monitoring Consortium (rmc.usc.edu) are particularly relevant to this project. The following is the ICS management structure.

The existing project and the efforts proposed in the work have synergistic effects and can lead to advances beyond the described goals of the project. The broad technical topics of the proposed research program, each of which is directly related to many ongoing efforts in the centers outlined above or within our other programs, renders USC an ideal place to conduct such a study. Among the broad range of technical disciplines are: reservoir engineering, including reservoir simulation, characterization, seismology and earthquake engineering, geophysical monitoring, civil and environmental engineering. The laboratory and computer facilities of our different research centers will be at our disposal. For this project we will mainly use the computational resources and facilities with super computing power at engineering school and university level.

We expect to have two advisory Boards: Strategic Advisory Board (SAB) and Technical Advisory Board (TAB). Both SAB and TAB will be populated with representatives from different sponsoring entities and USC faculty. SAB and TAB activities will be supported by two USC faculty members: Dr. Don Paul the director of USC Energy Institute and former CTO of
Chevron for SAB and Dr. Tom Jordan, executive director of Southern California Earthquake Center for TAB.

C.2 Qualifications of Key Personnel
The principal investigators are imminently qualified to conduct research on reservoir connectivity characterization and geophysical monitoring.

Dr. Fred Aminzadeh is a professor of petroleum and electrical engineering at USC and director of USC Reservoir Monitoring Consortium. He is also associated with USC Energy Institute and leads its Global Energy Network. He served as president of SEG from 2007 till 2008. Dr. Aminzadeh previously worked for Unocal with both technical and management responsibilities. Before joining USC he was the president and CEO of dGB Earth Sciences USA. He also worked for about 20 years for Unocal in various positions including manager of geophysical technology. He has a Ph. D. from University of Southern California. His thesis dealt with the analysis of layered earth media. He is a fellow of IEEE, member of Russian Academy of Science, a member of Azerbaijan Oil academy, and National Research Council’s Committee on Seismology. He has served as a member of DOE’s Unconventional Resources Technology Advisory Committee, the chairman of the SEG Research Committee and chairman of the advisory board of Western Standard Energy Corporation. He has three patents and an extensive list of publications in diverse areas including eleven books such as those on Reservoir Characterization, Petroleum Geology of South Caspian Basin, 3-D Seismic Modeling Advances in Seismic Data Processing, Geophysics for Engineers, and Petroleum Industry Applications of Pattern Recognition and Soft Computing. One of his papers (with the world renowned seismologist K. Aki) directly deals with understanding the seismic attributes that can characterize earthquake with potential prediction possibility using the pre-cursor data.

Dr. Behnam Jafarpour joined USC Viterbi School of Engineering faculty as an assistant professor of petroleum and electrical engineering from Texas A&M University where he served as an assistant professor for about four years. Prior to that he completed his PhD and SM degrees at MIT, where he spent a number of years on multidisciplinary research in the general areas of parameter estimation, inverse modeling, and reservoir characterization. He has published more than 20 journal articles related to reservoir engineering and the subject of this proposal. His specific areas of expertise include geostatistical reservoir modeling and characterization, reservoir parameterization and model reduction, production data integration, and closed-loop management of smart oilfields. He is currently directing the research projects
of eight graduate students and a postdoctoral research associate. He serves as a Co-PI in two DOE projects: one with Dr. Ahmad Ghassemi (Petroleum Engineering, Texas A&M University) on geothermal reservoir characterization with a support amount of $1,025,000 and one with Dr. Akhil Datta Gupta (Petroleum Engineering, Texas A&M University) and Dr. Yalchin Efendiev (Mathematics Department, Texas A&M University) on uncertainty quantification in subsurface characterization with a support amount of $877,000.

**Dr. Charles Sammis** is professor of geophysics with a joint appointment in the materials science department. He has published extensively on the fractal analysis of seismicity and fault networks, and on the predictability of earthquakes. He is also an expert in micromechanical damage mechanics with special application to the seismic coupling of underground nuclear explosions and the mechanics of earthquakes. He was elected Fellow of the American Geophysical Union in 2007.

**Dr. Meghan Miller**, Meghan Miller is an assistant professor of geophysics and her expertise lies in tectonophysics and observational seismology. She has published many papers focusing on imaging of Earth’s structure and understanding tectonic processes using earthquakes as a data source.

**Dr. Lucio Soibelman** obtained his Bachelor and Masters Degrees from the Civil Engineering Department of the Universidade Federal do Rio Grande do Sul, Brazil. He worked as a construction manager for 10 years before moving in 1993 to the US where he obtained in 1998 his PhD in Civil Engineering Systems from the Civil and Environmental Engineering Department at the Massachusetts Institute of Technology (MIT). In 1998 he started as an Assistant Professor at the University of Illinois at Urbana Champaign. In 2004 he moved as an Associate Professor to the Civil and Environmental Engineering Department at Carnegie Mellon University (CMU) and in 2004 was promoted to Professor. In January 2012 he joined the University of Southern California as the Chair of the Sonny Astani Department of Civil and Environmental Engineering. During the last 12 years he focused his research on advanced data acquisition, management, visualization, and mining for design, construction, and operation of advanced infrastructure systems. He published over 100 books, books chapters, journal papers, conference articles, and reports and performed research with funding from NSF (NSF career award and several other NSF grants), NASA, DOE, US Army, NIST, IBM, Bosch, IDOT, RedZone Robotics among many others funding agencies. He is the current chief editor of the
American Society of Civil Engineers Computing in Civil Engineering Journal. His areas of interest are the use of information technology for economic development, process integration during the development of large-scale engineering systems, information logistics, artificial intelligence, data mining, knowledge discovery, image reasoning, text mining, machine learning, advanced infrastructure systems, sensors and sensors networks, streaming data, and Multi-reasoning Mechanisms.

Dr. Roger Ghanem is Professor in the Departments of Aerospace & Mechanical Engineering and Civil & Environmental Engineering at USC. He has expertise in probabilistic mechanics and computational science with emphasis on uncertainty quantification (UQ) and model validation. His recent research, relevant to the present effort, explores linkages between UQ, reduced models, and multiscale behaviors of physical phenomena. He currently serves on the NRC committee for exploring the mathematical foundations of UQ and V&V. He also serves as programs director and chairman, respectively, for the UQ committees in SIAM and USACM.

C.3 Quality and Suitability of Facilities, Equipment and Materials
The Viterbi School of Engineering at USC is well equipped to conduct the proposed research, with state-of-the-art facilities and centers for computational and monitoring work. World-class computer facilities are available for the data analysis and modeling work planned in the project. The USC Reservoir Monitoring Consortium (RMC) is involved in research areas spanning different technical and operational challenges associated with oil and gas industry from exploration and production. USC RMC currently uses two different software for seismic interpretation: OpendTect, which is open source software with the capability to develop new programmable modules depending on the problem in hand, and SMT kingdom software which is extensively used in oil industry. We plan to use this to further evaluate the seismic, well logs, or micro-seismic data within the study area. RMC currently uses two servers (Windows and Linux platforms) for its computing as well as database requirements. Currently, there is good collaboration between RMC team, Cisoft group, and the geosciences department at USC. This collaboration will help us better handle the geophysical and geologic data that we obtain in the future as part of our project.

Seismological capabilities at the Southern California Earthquake Center
The Southern California Earthquake Center (SCEC) is a community of over 600 scientists, students, and others at over 60 institutions worldwide, headquartered at the University of Southern California. SCEC is funded by the National Science Foundation and the U.S.
Geological Survey to develop a comprehensive understanding of earthquakes in Southern California and elsewhere, communication of useful knowledge for reducing earthquake risk, and understanding key aspects of earthquake behavior. The SCEC scientists involved in this proposed project bring an expertise in the characterization of seismicity, tectonics, seismic imaging, source mechanics, and earthquake hazard analysis that has been developed over 30 years of studying tectonic earthquakes.

Civil/Environmental Engineering Laboratories

Co-PI Ghanem is closely involved with the DoE/SciDAC QUEST Institute for Uncertainty Quantification for which he serves as deputy director. This will provide the proposing team with ready access to state-of-the-art resources and capabilities for carrying out stochastic calibration, uncertainty quantification, Bayesian updating, and model validation for large-scale computational models. Furthermore, the USC team has long-standing experience utilizing the high-performance computing resources at USC including mathematical analysis and data analysis software.

References


