Hazards SEES: The Risk Landscape of Earthquakes Induced by Deep Wastewater Injection

1. VISION

The United States is experiencing a major expansion of domestic oil and gas production. These processes produce high volumes of water, and the energy boom has been accompanied by a major increase in wastewater disposal by injection [1,2]. There is growing evidence that deep injection for wastewater disposal can generate earthquakes under certain conditions [3]. Injection-induced earthquakes are thought to be responsible for the uptick of earthquakes some places, like Oklahoma, which experienced more earthquakes larger than M 3 in 2014 than California [4,5]. Although there is much ongoing research related to the potential impacts of the increased oil and gas production on water and air quality, little work has been done to understand how injection wells affect seismic risk, creating substantial uncertainty for communities, industry and regulators. As illustrated in Fig. 1, our CU Collaboratory for Induced Seismicity (CCIS) will develop the geoscience, social science and engineering understanding, models and methods needed to quantify risks associated with injection-induced seismicity and to evaluate strategies for sustainably managing and mitigating these risks. Although we will focus on the increased seismicity generated by hydrocarbon recovery activities that are central to the U.S. energy boom, other activities (*e.g.* mining, CO_2 sequestration, reservoir impoundment [6,7]) can also create earthquakes. These phenomena challenge the paradigm of earthquakes as "acts of God." The development of a sustainable energy system for future generations requires better understanding of the impacts of these activities.

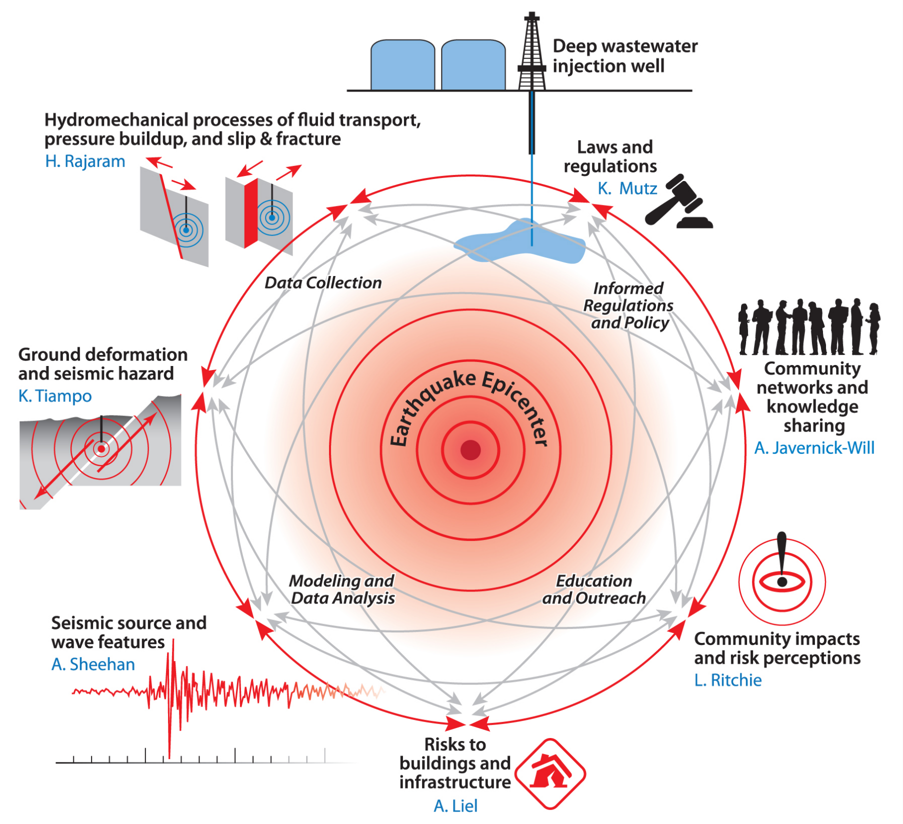

Figure 1. Organization of CU Collaboratory for Induced Seismicity (CCIS) research considering a coupled system of natural, built and human (social) environments.

CCIS will probe the mechanisms by which injection wells induce earthquakes, the potential for these earthquakes to cause damage to the built environment, and the social and economic impact of induced earthquakes, expanding our knowledge of the complex interactions of the natural (Theme I), built (Theme II) and human (Theme II) environments in the creation and management of induced seismicity. Theme I involves seismic monitoring and analysis of satellite measurements of surface deformations around injection wells and development of coupled hydromechanical models. Taken together, these efforts will create new understanding of the source characteristics of induced earthquakes and the fluid transport and rock rupture processes that create these events, improving understanding of the ways in which source characteristics of induced earthquakes are different from tectonic events. Theme II moves beyond the notion that induced earthquakes are not large enough to cause damage to the built environment, developing new fragility and hazard models to proactively assess this risk. Theme II also explores how risk models can be revised if monitoring or other regulatory actions are pursued. Theme III addresses uncertainty about oil and gas development and induced seismicity in affected communities, examining how induced seismicity is reflected in communities' risk perceptions, knowledge sharing, and stresses. Theme III also responds to the need of state regulators and industry for better information about regulatory alternatives. The research is grounded in four case study communities in Colorado and Texas. This proposal is based on a proposal submitted to the previous Hazards SEES call. Major changes have been made in team composition and research themes to respond to reviewer comments.

1.1 Intellectual Merit

The research plan proposes a holistic study of earthquakes induced by deep wastewater injection, tracing fluid flow, earthquake initiation and ground shaking characteristics to probabilistic damage models, to extensive social science research on community impacts with respect to risk perceptions, social cohesion, community networks, and knowledge sharing. The research will investigate for the first time current regulations on induced seismicity, and examine how regulations impact and respond to the geoscience, engineering and community processes. These goals will be accomplished through in situ and participatory empirical research and design, combined with data collection from seismological and satellite instruments and multi-scale models. In doing so, the research will transform the understanding of the sustainability of the coupled natural-human-physical systems that affect and are affected by earthquakes induced by deep wastewater injection, creating new approaches for mitigating and managing these risks.

1.2 Broader Impacts

The proposed research will provide vital knowledge to local communities, regulators, and the oil and gas industry about the tradeoffs associated with wastewater injection. This knowledge will be packaged in a number of impactful products, including guidance documents on seismic monitoring, a science-based model regulation that will be used to inform state and local regulatory decisions, and seismic hazard tools for use by industry, insurers and others. This information can be used to manage risks associated with injection-induced seismicity to foster more sustainable development of energy. The committed External Advisory Board (EAB), composed of representatives from regulators, industry and academia, will help the research team guide the development of research products and lead the transfer of knowledge and products to key decision makers. The project will also train a cohort of students and postdocs to bridge across disciplines to create scientific tools to model and evaluate the risks associated with induced seismicity and to better communicate these risks. The team has a high representation of women in science and engineering, which will be leveraged to recruit and mentor underrepresented students.

2. CONTEXT

The dramatic recent increase in domestic petroleum and gas extraction is due in part to the development of hydraulic fracturing and horizontal drilling methods that stimulate oil and gas production by injecting fluids underground to initiate fractures [2], and extraction methods that bring up formation water as a byproduct (called 'produced water'). There is some evidence that fracturing itself induces earthquakes [3], but the main culprit is large volumes of wastewater, which is often disposed of through injection into deep disposal wells, and can induce earthquakes. There are well-documented cases in which the large-scale injection of fluids has induced earthquakes. For example, strong correlation was documented between the injection of chemical waste fluids and seismicity observed at Rocky Mountain Arsenal near Denver [8]. The mechanics of induced seismicity can be represented by a Coulomb failure criterion, wherein an increase in fluid pressure within a fault or fracture plane decreases the effective normal stress and thus, the frictional resistance, inducing slip by shear [9–11]. Nevertheless, among thousands of injection wells in the U.S., only a few have induced earthquakes. Earthquake occurrence is affected by the characteristics of the injection and of the underlying rock [3,12]. Induced earthquakes are typically identified by high spatial and temporal correlation between injection and earthquake(s) [13].

The only national policy for induced seismicity is the Department of Energy's protocol for development of enhanced geothermal systems [14]. Regulation of underground injection wells is the responsibility of the EPA, under the Safe Drinking Water Act. Class II wells are those related to oil and gas activities (~ 87% of all wells) [3]. EPA's regulation focuses on protecting below-ground sources of drinking water. In some states, the EPA has ceded primacy to state agencies. States have responded in a variety of ways to known or suspected induced earthquakes. In Arkansas, the state regulator ordered existing wells be shut down and a moratorium on new wells in part of the state, after a group of earthquakes in 2009 and 2010 that were highly correlated with injections [15]. This is a so-called "traffic light" policy, in which injection is stopped or slowed if noticeable seismicity occurs [3,14]. The operators of the Geysers, CA geothermal steam field have taken a different approach, establishing a procedure whereby building owners submit claims for damage from to induced events [3]. Review of legal precedents [16] associated damage from mining and other induced ground vibrations, and suggest that legal mechanisms of trespass, nuisance and others could be used to pass liability to the injectors for certain types of damage, but this has not been tested in the contemporary context.

3 RESEARCH PLANS

This study will examine the risks of injection-induced seismicity in the context of four communities in two states: Greeley and Platteville, Colorado, and Timpson and Snyder, Texas. The energy industry is a major contributor to both states' economies [17], both states have a large number of Class II Wells, and sparse tectonic seismicity, as illustrated in Fig. 2. The inclusion of multiple communities in our study will enable comparisons based on different geologic, social, political, and policy environments. All of case study communities are near multiple injection wells. Populations of the case study communities range from about 1,000 in Timpson to 97,000 in Greeley. Platteville and Greeley have experienced especially significant gains in population in recent years due to the boom associated with oil and gas activity. The state regulators, the Colorado Oil and Gas Conservation Commission (COGCC) and the Texas Railroad Commission, have developed injection-permit policies that address the risk of induced seismicity [18,19].

Colorado has experienced some of the best-documented historical cases of injection-induced seismicity [8,20]. Greeley is adding to that database, with a widely felt earthquake in 2014 followed by industry, regulators, and academic researchers (including co-PI Sheehan's group) working together on close monitoring and aggressive mitigation efforts [21,22]. The proposed work will leverage and expand the seismic monitoring data with a uniquely interdisciplinary context. Platteville is close to Greeley, but has not experienced induced seismicity, providing a useful counterpoint for investigation. Of the induced earthquakes that have occurred in Texas, the most damaging was a M 4.8 event near Timpson, with shaking and damage documented by [23], and ground deformations monitored by SP Tiampo's group. The community of Snyder, Texas has experienced earthquakes induced by oil and gas activities for at least two decades [24], including under the present boom of unconventional oil and gas development.

Research Theme I: Induced Seismicity and the Natural (Geologic) Environment

There is insufficient information regarding under the conditions in which injection-induced seismicity generates damaging earthquakes. The first research theme employs seismic monitoring, statistical seismic analyses, surface deformation measurements, and coupled hydromechanical models to explicate mechanisms and subsurface characteristics that affect the occurrence of injection-induced seismicity and to characterize the source features of induced earthquakes.

I.1 Seismological Characteristics of Induced Seismicity (Lead: Sheehan, with Tiampo)
Work to systematically characterize the source properties and ground shaking of induced events is an area of active research (*e.g.,* [25]), and it is debated how different induced earthquakes may be from tectonic events and how the rate and volume of the injection may impact these characteristics. The severity and characteristics of an earthquake depends on the source properties of the earthquake events (*e.g.,* magnitude, frequency, stress drop) and on the near surface geology. Knowledge of the spectral properties

and the magnitude-frequency relations of earthquakes are needed to better estimate the impact of possible events. Though not induced, the 2011 Christchurch earthquake is an example of a relatively moderate M_w 6.3 earthquake that had catastrophic consequences because of its shallow depth, high stress drop, and proximity to vulnerable infrastructure [26,27].

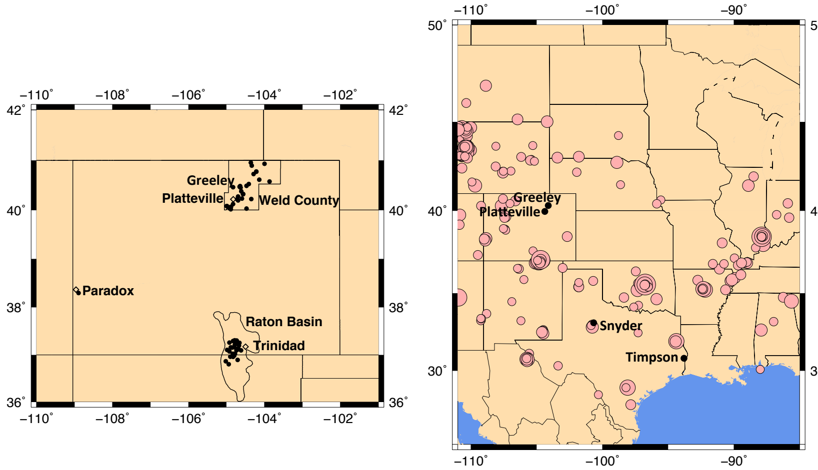

Figure 2. Maps showing (a) Class II injection wells around selected communities in Colorado and (b) earthquakes (pink dots) with $M_w \geq 3.5$ from 2000 – 2014 in the south central U.S. The locations of the case study communities are shown with black dots in (b).

Research Questions: *(i) How does seismicity respond to modification in injection parameters?*

(ii) *What are the seismic source characteristics of induced earthquakes? How do they compare to tectonic and volcanic earthquakes?*

(iii) *What are the spatial, temporal, and size patterns associated with induced earthquake sequences? How do these patterns relate to the fluid flows measured in Theme I.2?*

(iv) *What are the unique characteristics of ground shaking generated by such events?* Characteristics of interest include ground motion frequency content and intensity.

Research Approach: Our efforts will focus on two tasks: (1) continued microseismic data collection at the site of suspected induced seismicity at Greeley, CO, and corresponding analysis of concurrent injection and geologic information associated with the unique mitigation experiment by the regulators; (2) characterization of the properties of induced as compared to tectonic earthquakes.

We describe the Greeley earthquake and seismic deployment and monitoring efforts first. On May 31, 2014 a M 3.2 earthquake occurred east of Greeley, CO. Weld County is the locus of significant oil and gas production, and hosts many Class II injection wells. The Greeley earthquake was felt over 60 miles away from the epicenter. In response to this earthquake, Sheehan's research group deployed six seismometers and one accelerometer beginning three days after the earthquake [21,22]. Earthquakes were located in a small cluster (~2 km radius) centered near a Class II injection well (NGL Well C4A). The injection company, NGL Energy Partners LP, had been injecting waste fluid into the deepest sedimentary formation of the Denver Basin at rates as high as 350,000 barrels/month for less than a year. The earthquake and subsequent seismicity sequence recorded by Sheehan's group led to a decision by the COGCC to recommend a temporary halt to injection at that well. After a 20 day shut-in period, injection at was allowed to resume at a rate of 5000 barrels per day, with continued seismic monitoring from our group. Seismicity rates have remained low but not uniform, and injection rates have been allowed to increase. The shutdown of well C4A and resumption of smaller injection volumes provides a unique opportunity to directly evaluate the seismicity's relationship to well operations. Matched filter methods have been used to examine seismicity near the well in the time preceding the June 1 felt event, and a number of events were found starting just a few months after injection at C4A started; no events were observed prior to the start of injection at NGL Well C4A.

The proposed work for the Greeley and nearby Platteville case studies will involve continued monitoring for new seismicity analysis (this theme and Theme I.2), geodetic observations (Theme I.2), hydromechanical modeling (Theme I.3), and strong ground motion assessment (Theme II.1). This grant will maintain three of the stations in the Greeley network for an additional year and expand the network using the other 3 stations to investigate high rate injection wells in nearby Platteville that are aseismic. Seismic analysis will include event detection (matched filter methods used for detection [28,29], event location using a variety of advanced algorithms including double difference and Bayesian methods [30–33], source studies (including focal mechanisms, stress drop, and spectral characteristics), statistical seismology, and analysis of acceleration spectra.

For the second task, we will explore differences between tectonic and induced earthquakes. We will being by performing a seismological analysis of the spectral properties of all earthquakes with $M_w > 3.5$ occurring in the U.S. between 110 and 90° west, which are well-recorded by the USArray seismic experiment (2005-present) [34], supplementing the USArray data with other seismograms as available. In addition, we will tabulate previously published data on induced earthquakes throughout the midcontinent, including catalogs for USGS, state networks, and other sources, and combine them with the data obtained from the Greeley seismic deployment and subsequent analysis. In catalog development, we will account for larger location uncertainties and different magnitude cut-offs in older catalogs. We will make use of aggregate earthquake catalogs to examine background rates of seismicity in our four case study areas and the broader central U.S. region. We will determine seismic stress drop, which is defined as the difference in stress across a fault before and after an earthquake and can be estimated using the spectral characteristics of seismograms, for all of the earthquakes with $M_w > 3.5$ using an empirical Green's function method [35,36]. Focal mechanisms will be used to estimate the local faulting regime (extensional, etc.) and state of stress, using published seismic moment tensors [37] where available. These catalogs will be used to complete in-depth statistical seismology analysis of seismic rate changes and properties (GR distribution, b-value, aftershock decay, among others) for the case study locations, including time-dependent variations in space for correlation with the fluid patterns studied in Theme I.2.

I.2 Surface Deformation and Subsurface Structure (Lead: Tiampo)

New satellite-based geodetic techniques for measuring surface deformations have the potential to greatly improve our understanding of the fluid transport processes that lead to injection-induced seismicity. Satellite-based geodetic techniques can provide non-invasive, frequent, long-term, cost-effective monitoring of Earth's surface and associated subsurface processes. One technique, differential interferometric synthetic aperture radar (DInSAR) uses the phase change of radar reflections from Earth's surface to quantify changes in the position of those reflection pixels and, under certain conditions, can detect surface motion with accuracies of a few millimeters. Current SAR technology can provide surface height measurements with a dense spatial resolution (on the order of meters to tens of meters) about once per month. With the upcoming European Space Agency (ESA) and Canadian Space Agency (CSA) constellation missions, near real-time data will become available on an almost daily basis [38].

DInSAR has been used recently to by Tiampo, among others, to detect subsurface changes in water volume by quantifying the associated ground surface height changes [39–41]. These studies have focused on surface deformation due to the anthropogenic evacuation of groundwater from underground aquifers [42–45], providing knowledge of the relationship between pumping rates and the associated subsidence to define the nature of the subsurface structure and the associated aquifer. Other recent DInSAR studies have identified mining induced surface deformation near Rice Lake, Saskatoon using CSA RADARSAT-2 synthetic aperture radar images [46], and uplift at the Salah, Algeria CO_2 storage facility from Envisat DInSAR studies [47]. In the latter, measurable surface displacements and the resulting pattern of deformation was inverted to model the flow within the reservoir and a seismically detected fracture/fault zone that intersected that reservoir. Barnhart *et al.* [48] modeled the pre-, co- and post-seismic deformation related to the 2011 Trinidad earthquake (M~5.3), which was potentially induced by oil and gas development in southern CO. These DInSAR investigations of injection processes [46,47] provide strong evidence that these satellite-based geodetic methods can be effective in monitoring the energy-related hydraulic fracturing and fluid injection or withdrawal.

Research Questions: (i) *What is the subsurface migration pattern of injected fluids at the 4 test sites?*
(ii) *Is that migration controlled by existing structures or fracture planes?*
(iii) *How is that fluid migration related, spatially and temporally, to the seismicity*?

(iv) *How do the critical parameters of the underlying medium, such as permeability and pore pressure, correlate to the occurrence of induced seismicity?*

Research Approach: Our study will employ InSAR analysis with C-band images from the Envisat and Sentinel satellite systems. DInSAR deformation maps from Sentinel provide excellent spatial coverage due to high spatial resolution, short orbit repeat times, and small spatial baseline variability and will allow us to produce a larger number of highly coherent interferograms over a shorter period of time. These results will be used to investigate the depth and spatial extent of fluid migration through a number of steps: 1) Request and acquire archived images from complete ENVISAT, Radarsat2 and Sentinel acquisitions, beginning initial analysis for baseline records. 2) Use GAMMA software to prepare DInSAR images for specific time periods related to induced seismicity and ongoing injection activities. 3) Apply advanced DInSAR analysis (permanent scatterer, SBAS, polarimetric InSAR analysis (coherence and PPD) and MSBAS) to characterize spatial and temporal occurrence of local and regional deformation.

This study will provide detailed information on the surface deformation associated with injection (or extraction) process into subsurface reservoirs at the case study sites, including migration of fluid through known or unexpected fractures and faults, and the rate and direction of lateral flow. Advanced inversion techniques using one or more of several well-characterized models will relate groundwater changes to surface deformation (selection of which will depend on the nature of the subsurface structure at a given location) [49–51]. Inversions for these relatively simple models of aquifer and subsurface structure will provide important constraints on the nature and location of fracture networks, porosity, permeability, bulk modulus and pore pressure. The results from this project will better constrain the critical parameters for the advanced hydromechanical modeling in Theme I.3.

I.3 Hydromechanical Processes Controlling Induced Seismicity (Lead: Rajaram, with LANL)
Fully coupled numerical hydromechanical models, corroborated through seismological and geodetic measurements, have the potential to improve understanding of where and when earthquakes may be induced to identify high risk areas. Reliable estimation of the critical fluid pressures that will induce slip at a specific location is hampered by the difficulties in accurately estimating the horizontal principal stresses in the local rock, and uncertainties in fracture and fault properties. Zoback and Zoback [52] showed that the state of stress and fluid pressure at most U.S. locations is close to the critical condition. Yet, seismicity has not been induced at all or even most fluid injection sites and unexpected seismicity has been encountered even after injections ceased at some sites [10]. Although several previous studies have demonstrated the relationship between critical fluid pressures and seismicity by post-analysis [4,53–55,5], induced seismicity has almost never been predicted. Despite this cautionary fact, numerical models of coupled hydromechanical behavior offer a promising tool for understanding of induced seismicity [3,10], in the sense of earthquake forecasting as opposed to earthquake prediction (the distinction is addressed by [56]). Hydromechanical models have successfully captured fracture stimulation by fluid injection in enhanced geothermal systems [57–59] and fault reactivation during CO_2 injection [60].

Research Questions: (i) *What is the initial stress state at the site*? *What are the pre-injection properties of structural features (e.g. fault and fracture planes) susceptible to slip?*

(ii) *What is the spatio-temporal distribution of fluid pressure increases at the site of interest? What is the volume of rock/faults subjected to high fluid pressures?*

(iii) *What is the surface-deformation signature associated with fluid injections?*

Research Approach: This theme will develop high-resolution hydromechanical models for fluid pressure diffusion, geomechanics, and coupling between deformation and permeability evolution in the subsurface formations where seismicity is triggered. We will also develop geomechanical models of overburden deformation to quantify surface deformation in response to deep fluid injection. These models will be developed against the backdrop of data on seismicity and surface deformation generated under Themes I.1 and I.2 respectively.

Unlike most previous modeling of injection-induced seismicity, which focus on calculating pore pressure increases, we propose fully coupled hydro-mechanical computations, wherein feedbacks between pressure-induced deformations, alteration of stress fields, and dynamic properties (both hydraulic and mechanical) of faults/fractures are explicitly captured. We will use *PFLOTRAN*, a massively parallel single and multi-phase flow simulator for fluid flow [61]. One of the core developers of *PFLOTRAN*, Dr. Satish Karra, is a collaborator on this project, as described in the attached letter. *PFLOTRAN* has been augmented with significant capabilities for modeling flow in discrete fracture networks, which are also relevant for modeling faults. For fault modeling, we will use *PyLith* [62], an open-source finite-element geodynamics code, with capabilities for parallelization. Advanced gridding capabilities provided by the LANL meshing tool *LaGriT* will facilitate the creation of complex meshes for fault and fracture networks. To facilitate computational tractability, we propose a hybrid-multi-scale modeling approach that permits different levels of resolution and detail in different sub-regions within a site. Our models will incorporate deformation-dependent hydraulic and mechanical properties of fractures, representing nonlinear normal stiffness-deformation behavior and propensity for shear failure/activation. Fluid flow equations will be based on the Darcy equation in equivalent porous medium regions, and also incorporate linear or nonlinear fracture flow regimes. Rajaram has modeled flow and transport in fractured rock in previous work, including evolving fracture properties [63–67]; and represented heterogeneity in porous and fractured media stochastically .

Hydromechanical models will be used generate representations of fluid pressure changes and surface deformation for comparison with observations described in Theme I.2, and of slip events, which are correlated to the magnitude-frequency distribution of seismic events [68], for comparison with the catalogs and rates determined in Theme I.1. We will use Monte-Carlo simulations with the coupled hydromechanical models to iteratively refine the site-specific subsurface models based on observations of surface deformation and seismicity. We will initially use Paradox Valley (Fig. 2a) as a test case to refine the modeling framework. The extensive observations and characterization of induced seismicity and injection history at Paradox Valley [69,70] provide attractive targets to guide model development. The models will then be applied to evaluate seismicity at the other case study sites in the proposed research. At Greeley, well completion and injection data are available from the COGCC for the NGL SWD-C4A well. The general geology and petroleum geology of the basin is described in [71,72], and will serve as a starting point for building hydromechanical models. Preliminary discussions between co-PI Sheehan and Noble Energy suggested association of seismicity with NE-SW and NW-SE trending structures, but specific faults along which seismicity was triggered have not been identified yet. Hydromechanical modeling in combination with continued seismic monitoring (Theme I.1) and surface deformation measurements (Theme I.2) will help to improve understanding of induced seismicity leading up to the Greeley earthquake, and projection of future trends in seismicity in the area. We will employ probabilistic representations of formation properties, fault locations, areas, and properties; and refine these representations through extensive Monte-Carlo simulations and other inverse methods [47]. A similar approach will be pursued with the other sites, beginning with petroleum/geology references, and augmenting models information from surface deformation measurements and monitoring, where accessible from seismic arrays.

Research Theme II: Induced Seismicity and the Engineered Landscape

One significant source of uncertainty related to induced seismicity is the potential for injection-induced events to damage existing buildings and infrastructure that are located near the well sites. The risk of damage, and the associated losses associated with the time and money needed to conduct repairs, depends on the characteristics of the induced earthquake, the features of ground shaking at sites where structures exist, and the fragility of the built infrastructure to such events. To our knowledge, there have been no systematic efforts to examine risks to engineered structures associated with injection-induced seismicity.

II.1 Fragility of Buildings and Building Components in the Context of Induced Seismicity (Lead: Liel, with USGS collaborators)

Although the statement that injection-induced earthquakes are not large enough to damage buildings and infrastructure is often repeated, several recent induced earthquakes have caused damage to homes and structures [23,25,73,74]. The likely-induced 2011 Trinidad, CO M_w 5.3 earthquake [73] damaged 46 structures (two severely enough to be condemned) [74,75]; the 2011 Oklahoma M_w 5.6 earthquake injured

2 people and damaged 14 homes [76]; in Timpson, a May 2012 earthquake that is thought to be induced damaged numerous chimneys, fireplaces and brick veneer [23]. Building damage has also been observed in earthquakes induced by enhanced geothermal systems, which seem to have similar characteristics to injection-induced events. In Basel, Switzerland, a M_w 3.4 earthquake in 2006 caused an estimated $9 million in damage [3,77]. The types of damage observed in these events do not threaten life safety, but burden communities with significant repair costs where earthquake insurance is uncommon [86]. Uncertainty about the potential for damage has contributed to uncertainty for industry and regulators [78]. The aforementioned Swiss geothermal system was abandoned due to excessive seismic risk [77]; in the U.S., injection wells in Ohio, Colorado and Arkansas have been shut down or curtailed due to concerns about seismic activity [15,22,79]. Moreover, the shaking has contributed to community concerns about oil and gas development [19].

Induced events challenge our understanding of earthquake risks in a number of ways. First, the ground shaking characteristics may be unlike tectonic events, leading to different patterns of damage than naturally occurring events. In one of the only studies examining this issue, Hough [25] collected "Did You Feel It?" reports from the USGS website from 21 induced and tectonic earthquakes in the central U.S., finding that induced earthquakes may be less damaging than tectonic earthquakes of the same magnitude. Research is needed to corroborate or reject this hypothesis and to explicate the relationship between source characteristics, ground shaking patterns and damage for induced earthquakes. Second, the potential for damage under low magnitude earthquakes in general is poorly quantified. Little is known about the fragility of chimneys, veneer and other non-seismically designed building components to ground shaking. These fragility relationships are essential to the risk assessments described in Theme II.2.

Research Questions: (i) *Are the characteristics of structural response under induced earthquake similar to the response under tectonic earthquakes?*

(ii) *How fragile are buildings, building components and infrastructure to small-magnitude, shallow earthquakes of the type produced by injection-induced earthquakes?*

Research Approach: We will investigate the characteristics of damage to building and infrastructure through nonlinear dynamic structural response simulations and loss assessments within the framework of performance-based earthquake engineering [80]. The first task of the proposed research is to characterize the engineering properties of ground motion recordings from injection-induced earthquakes. This task requires collecting a set of recorded ground motions from induced earthquakes and, for comparison, small magnitude tectonic earthquakes. PI Liel's research team already has collected accelerometer recordings from more than a dozen earthquakes induced by wastewater injection and enhanced geothermal activity. Collaboration with Sheehan and the activities of Theme I.1 have and will be critical to continuing to identify and retrieve recordings. Once a database of ground motions is developed, the focus will be on quantifying measures of ground motion intensity, *e.g.,* peak ground acceleration or peak ground velocity, response spectra, and duration, which are known to be important predictors of structural response and damage [81–83]. The properties of these recordings will be compared to ground motions recorded from natural (tectonic) events with similar magnitude, distance and site parameters to evaluate whether the differences in source (*i.e.,* induced vs. tectonic mechanisms) affect the critical engineering properties of ground motions. Comparisons will also be made between ground motions from injection-induced and those induced from enhanced geothermal systems and others activities.

The second task will use analytical simulation models of buildings and building components to determine the fragility of these systems to induced earthquake events. This effort requires the team to develop of nonlinear models of structures and non-structural elements of the type that have been damaged induced earthquakes, including chimneys, unreinforced masonry buildings and water piping systems. A preliminary finite element model for type masonry residential chimneys in Timpson, TX is being developed in Liel's group. When completed, these models will have material and geometric nonlinear features such that they are capable of capturing the progression of damage that may occur when subjected to acceleration time histories measured during seismic shaking [84,85]. Where possible, modeling approaches will be validated against earthquake damage data; for example, documentation of masonry chimney damage in past events may be useful [86]. Initially, ground motion intensity will be represented by peak ground velocity, which is thought to be an important damage predictor for small magnitude events [87], and damage states will be defined by engineering variables, such as the level of peak strain in the structure. These fragility models will be used to interrogate the relationship between induced seismicity and building damage. Small-magnitude earthquakes have not generally been studied in the context of building or component fragility, so the study will examine whether there are systematic differences in fragility in the face of small magnitude tectonic versus induced events and, if there are, identify ground motion parameters that can be used to explain these trends. We will also examine how changes in material, geometry and connections of the component in question affects the fragility to identify the classes of structures that are most vulnerable to these earthquake events and the type of damage that is most likely to occur. Then, building fragilities will be redefined in terms of damage measures of more meaning to owners, insurers, and regulators, focusing especially on defining damage by the cost needed to repair different levels of damage. These repair costs will be obtained from building professionals in the case study communities and through surveys (conducted in conjunction with Theme III) of impacted building owners in case study communities.

II.2 Engineering Risk Assessments for Induced Seismicity

Better information about the risks of damage associated with induced seismicity from energy technologies is needed by the oil and gas industry [78,87,88], residents, insurance companies [16], and regulators [14] to improve risk management and mitigation. Seismic risk is the product of seismic hazard, which reflects the likelihood that ground shaking of a certain intensity occurs, and vulnerability, which relates to the capacity of the built environment to resist this shaking (quantified in Theme II.1). In its now conventional form, probabilistic seismic hazard analysis [61] requires input identifying all earthquake sources capable of producing damage ground motions and characterizes the events that could occur at these sources by magnitude, depth, and other key parameters. The USGS uses these methods to generate national seismic hazard maps that define values (*i.e.,* loads) used in seismic design [91]. However, it is not yet clear how induced earthquakes will be treated in this context, and what new seismic hazard tools are needed to assist regulators and industry due to their time-dependent and anthropogenic nature.

Only a very limited number of studies have evaluated seismic risk in the context of induced earthquakes. VanEck et al. [88] assessed seismic hazard to determine a maximum magnitude event that could be produced by oil and gas exploration in the Groningen oil field, which they suggest correlates to risk. Bommer *et al.* [87] combined ground motion prediction equations with assumptions about threshold fragilities of the building stock in El Salvador to define traffic light procedures at a geothermal field to avoid substantial building damage. Nygaard [78] proposes a qualitative risk assessment procedure that can be used to define risk zones to consider in siting and operation of injection wells and other activities.

Research Questions: (i) *What seismic hazard information, in terms of spatial and temporal scale, is most useful for different stakeholders (e.g., industry, regulators, insurers, etc.)? How does the inclusion of induced events change the seismic hazard at the case study locations?*

(ii) *What are the risks of damage to buildings and infrastructure due to induced seismicity?*

(iii) *How do traffic light policies, seismic monitoring programs, changes in injection rates or other regulatory actions influence assessments of risk?*

Research Approach: Seismic hazard analyses for the case study communities will rely on results from Theme I, which will develop statistics on key earthquake characteristics from seismic monitoring and a new earthquake catalog. The other pieces needed for seismic hazard analysis considering induced events, including ground motion prediction equations, will be adopted from others in collaboration with the USGS Seismic Hazard Mapping Team (see letter). The USGS team, using input from a recent workshop held in Oklahoma City and other collaborations, will provide guidance on the selection of the appropriate ground motion prediction equations, maximum magnitudes, and clustering approaches. We will use two approaches to estimate the probability of earthquake occurring given a particular injection rate. The first method will use statistics of potentially induced events with similar injection and geologic characteristics from the catalog of induced events assembled in Theme I.1, with the goal of estimating the conditional probability of different magnitude earthquakes occurring. The second method will employ the results of the Monte Carlo analyses using hydromechanical models (Theme I.3). A sensitivity study will examine which parameters are most important from the perspective of the assessment of seismic hazard, including varying the time frame and spatial smoothing to understand the implications of these assumptions.

We will then use finite element models of building, infrastructure and building components (Theme II.1) to assess the seismic risk of the prototype structures in each case study community. The seismic risk assessment will begin by considering tectonic earthquakes only. The outcome of the risk assessment can be represented by loss curves that show, for example, the probability that more than *$X* of seismic induced losses will be incurred over the lifetime of a particular structure. These losses are useful for a number of applications, including the setting of insurance premiums. The study will then develop modified seismic risk predictions for the same buildings accounting for the change in seismic hazard due to injection-induced, which can be compared to the baseline (tectonic) case.

We will also examine the influence of different regulatory policy actions identified in Theme III.3, such as 1) additional seismic monitoring and 2) halting or reducing injection rates through a so-called traffic light policy), on the risk assessment procedures and results. We will consider decisions about policy actions in the probabilistic risk assessment through use of Bayesian networks and influence diagrams in a similar approach to that proposed by [92] for a different application. The influence diagram permits consideration of decision alternatives of injectors and regulators, including how and what to monitor and how much to inject. The selection of decision alternatives to consider will be made in conjunction with the seismic monitoring activity of Theme I.1 and the regulatory analysis of Theme III.3. Monitoring activities in particular will be examined in terms of the value-of-information offered by various sensor types and locations. The results of these seismic risk assessment considering decision alternatives will provide one input to the discussion of model regulations in Theme III.3. Hazard and risk assessment outcomes will be prepared and presented in different forms to stakeholders in Theme III.2 to explore how and in what form the information is most useful.

Research Theme III: Induced Seismicity and the Human (Social) Environment

There remains a dearth of evidence regarding the impacts of the increase in U.S. oil and gas production and wastewater disposal wells on the social landscape of surrounding communities. The ways in which, and extent to which, communities respond to the potential risks of wastewater disposal and potential induced seismicity depend on factors such as their knowledge, risk perceptions, and capacity for collective action. To investigate these factors, a case-based methodology will be employed in Themes III.1 and III.2 in the four communities. In Theme III.3, the team will investigate regulatory alternatives for managing risks in the context of community, industry and regulatory constraints.

III.1 Community Impacts & Risk Perceptions of Induced Seismicity (Lead: Ritchie)
Controversy surrounding the latest technological advancements in oil and gas development is on the rise, but little is known about the relationship between how communities perceive the various risks of this development and how the development itself and perceived risks influence community stress and disruption. A limited but growing body of social science literature illuminates the differential environmental, social, and economic effects associated hydraulic fracturing and other unconventional energy development activities [93–107] built upon earlier studies of social impacts of energy development, including boom-bust cycles of rapid growth and decline and examinations of opportunity-threat dynamics [108–113]. As summarized by Ladd [96], supporters consider newer oil and gas development activities to be vital to U.S. energy security, reducing CO_2 emissions, producing jobs, and revitalizing the economy of rural areas. Opponents highlight the potential for environmental degradation, induced seismicity associated with drilling and wastewater disposal, and other negative impacts. More recent work, in particular, focuses on beliefs about connections between hydraulic fracturing and increased seismic activity [94,96,97,103,114,115]. These controversies both reflect and drive uncertainty in communities experiencing rapid development. These uncertainties can exacerbate existing social tensions, foster new forms of social disruption, and generate individual and collective stress.

The proposed study integrates three empirically-based theoretical approaches: 1) the *ecological-symbolic* perspective [116]; 2) the concept of a *renewable resource community* (RRC) [117–120]; and 3) the *conservation of resources* (COR) mode [120–124]. The ecological-symbolic concept addresses how communities interpret environmental trauma by focusing on disruptions between people and their habitats, as well as how these disruptions produce individual and collective stress. The RRC model has been used by Ritchie and others [104–107] to examine psychosocial stress associated with oil and gas development activities. The COR framework examines social impacts of hazards and disasters through the values identified by the resources "individuals strive to obtain, retain, and protect" [105–107,125].

Research Questions: (i) *How, and to what extent, do community attachment, identity, sense of place, and ties to the natural environment affect beliefs and attitudes about oil and gas development activities? Conversely, how and to what extent do these development activities affect community attachment, identity, sense of place, and ties to the natural environment?*

(ii) *How do individuals and groups in communities evaluate risks and benefits associated with oil and gas development activities? How are risks of induced seismicity considered the context of other risks?*

(iii) *What are the key factors influencing decision-making processes related to support/lack of support for oil and gas development? (e.g., Economic? Environmental? Information sources?) To what extent do concerns about induced seismicity influence these decision-making processes*?

(iv) *What, if any, is the relationship between beliefs about risks related to oil and gas development, individual and collective stress, and social disruption?*

(v) *What, if any, is the relationship between documented physical impacts of oil and gas development in a given area (e.g., induced seismicity, impacts on water quantity/quality) and perceptions of risk?*

(vi) *What, if any, is the relationship between beliefs about economic impacts of oil and gas development and perceptions of risk?*

Our approach to investigating these questions is consistent with previously-funded NSF and ongoing research by Co-PI Ritchie (e.g., see Gill et al. 2012, 2014; see also NSF Award #1000612 & #1248118).

Research Approach: This theme will employ a mixed-method approach patterned after Maxwell's [126] interactive research design model, collecting qualitative and quantitative data in the four selected study sites in Colorado and Texas. To address research questions *i-iii*, we will begin by conducting in-depth interviews with a purposive, representative sample of 60-80 key stakeholders (*e.g.,* formal/informal community leaders, industry representatives, activists, individuals from under-represented populations), 15-20 in each of the four study sites. Interviews will be audio recorded and transcribed for coding and analysis using qualitative data analysis software. These data will provide rich, narratives of different perspectives that will allow for comparisons both within communities and between communities. These findings will also be used to inform development of a survey instrument.

To address research questions *iv-vi*, and add to the data related to questions *i-iii*, we will conduct household telephone surveys with a random sample of 1,600 households (400 in each study site). Survey topics will include: i) knowledge about oil and gas development; ii) community attachment and sense of place; iii) risk perceptions and attitudes; iv) factors influencing decision-making; v) beliefs about resource gain and loss; vi) social disruption/ stress; and vii) sociodemographic information. Questions will emphasize attitudes and beliefs about induced seismicity, as well as broader issues related to oil and gas development. Survey data will be analyzed using standard statistical methods, both on a community-by-community basis and across communities. Results will be overlaid in a GIS system with data from the other components of the project (*e.g.,* seismic activity and earthquake damage- Themes I.1, I.2 and II.1, proximity to wastewater injection sites, and data on water quality/quantity from our collaborators at the AirWaterGas SRN) to identify additional correlations and trends.

Approval to conduct research with human subjects will be secured through CU's Institutional Review Board. To ensure that this theme supports the overall mission and goals of the project, we will collaborate with the broader project team to finalize the research design. For example, researchers working on regulatory aspects (Theme III.3) may develop questions exploring community members' knowledge of oil and gas regulation and preferences for public notifications. Research activities in Themes III.1 and II.2 will collaborate closely on the development of data collection instruments, share lists of potential interviewees, and, where appropriate, carry out interviews jointly.

III.2 Community Networks & Knowledge Sharing for Induced Seismicity (Lead: Javernick-Will) Communities grapple with decisions about whether to support or oppose oil and gas development in the context of the resource gains and losses they perceive from these activities. The information community members use to inform their decisions often originate from the social networks to which these community members belong. At this time, much of the information available to communities about hydraulic fracturing consists of poorly supported claims and counter-claims [108], and information about induced seismicity in particular is extremely limited. In these situations, when knowledge is not available, there is a "mismatch between the knowledge that science generates and the knowledge society needs" [109], which may lead to discontent and conflict [99]. With limited and contradictory information, community networks develop as social movements, or "loosely organized, sustained efforts to promote or resist change in society," relying "at least in part on non-institutionalized forms of collective action" [110]. These groups mobilize members and resources to gain legitimacy for their positions, while undermining the legitimacy of the opposing side [111,112]. These types of mobilized efforts, which include siting controversies, NIMBY movements, and LULUs, foster collective efforts towards sensemaking [110] and seek to link community members and organizations to build 'collective intelligence' [113,114].

Research Questions: (i) *Who are the actors and groups that are mobilizing at the community level in support of or opposition to the oil and gas development activities associated with induced seismicity? What are their beliefs, interests and concerns over these activities?*

(ii) *How are groups mobilizing and organizing to respond to these activities? Who is central to the debate? What are the characteristics of information sharing networks that develop?*

(iii) *What information about risks associated with these industrial activities, and specifically induced seismicity, is used and disseminated to support groups' interests and position?*

(iv) *How does the type of evidence used and network structure enable or constrain the development and achievement of their goals and behavior? How does this impact their legitimacy?*

(v) *How is the information about risks of induced seismicity generated from this research adopted and disseminated within these community knowledge-sharing networks?*

Research Approach: The proposed research will collect, analyze and assess information and knowledge dissemination about unconventional oil and gas development, with a particular focus on induced seismicity, within the four case study communities. The team will identify the community networks that form in support or opposition to these activities, the types of information about induced seismicity that are used, the source of this information, the mechanisms of information dissemination within these networks, and the influence of these knowledge sharing networks on risk perceptions.

To achieve these objectives, the research will identify and compile a list of community actors and their affiliated groups and organizations through: archival analysis of news, blogs and websites, and attending community meetings. Meanwhile, findings from Themes I and II about induced seismicity risks to the community, and data collected from Theme III.1 on the beliefs, attitudes, trust of information sources, and community characteristics, will be coded to each community and community member to determine the information that is available and being used by community members to build collective intelligence and to identify potential positive (*e.g.,* job creation) and negative (*e.g.,* seismic activity) focusing events [115] that may influence mobilization of community networks.

The research team will interview community actors using snowball sampling through a chain-referral method [116]. The team plans to begin with community members and groups that are active in debates over oil and gas development, conducting initial interviews with around 20 people in each community. The interviews will focus on group affiliations, the information used to inform risk perceptions and network mobilization, the source of the information, dissemination methods, and connections with other individuals and groups regarding oil and gas development and induced seismicity. Online questionnaires will then be administered to a larger group of community members identified through these interviews and the archival research. These questionnaires will contain a) ego-centric network questions to identify dyads, or connections, as well as the mechanics and dynamics of each identified connection (*e.g.* method of communication, information about induced seismicity, trust in information sources of induced seismicity, and other risks exchanged in these connections, and whether the connection is competitive or cooperative) [117], and b) person-centric questions, which will be used to code attribute data, including group affiliations and roles, risk perceptions, primary interests and concerns and events attended. From these emergent community networks, groups will be identified through both self-affiliation and social network analysis techniques, including subgroup algorithms to determine network structures within these communities [127,128]. Once these networks are analyzed, an additional 20 or so interviews will be conducted in each community with central actors and group leaders to determine each group's primary interests, strategies for gaining support/legitimacy, information collected and disseminated, and connections to and level of trust with other groups. Particular attention will be given to better understand how types of information about induced seismicity are used to legitimize or de-legitimize discussion of oil and gas development, given the abundance of non-peer reviewed information in existence. In addition, the study will attend to if and how mandatory or voluntary public notification or participation activities led by developers or regulators impact these networks and knowledge sharing.

The data collected will be transcribed/cleaned, coded and analyzed using a combination of social network analysis, descriptive statistics and qualitative analysis for each community. Sociograms will be created to visualize relationships among actors and groups and the networks will be analyzed for structure, including density, centrality, distance, brokerage and information flow. Documentation will also be analyzed to determine how and why the groups emerged, the information they are using, and how they are attempting to gain legitimacy and support. A cross-case comparison of the four communities will be used to explore how available knowledge about induced seismicity and other risks and benefits of oil and gas production influence collective intelligence, network mobilization, and strategic action. In addition, researchers will examine how network structure and evidence used support or constrain group level efforts and legitimacy across the communities. Where appropriate, these data will be analyzed in conjunction with data obtained through Theme III.1. For example, these networks will help to show the level of cohesion or social disruption within communities, which will also be addressed in telephone survey questions. Results of telephone surveys conducted in Theme III.1 will be included in the analysis here. Once data from this research on seismic hazards and risks from Theme II.2 becomes available in year 3, researchers will disseminate the information to the groups and actors within the community networks. After 3 months, we will then interview these participants to determine (a) if and how this information informed their perceptions of oil and gas development and wastewater disposal, and (b) if, how and to whom they disseminated this information. Ultimately, this research will better understand the types of information and information distribution mechanisms being used by community members to inform and mobilize in support or opposition to oil and gas development, and the community network and information-sharing structures that emerge in communities where these activities are occurring.

III.3 Regulatory Actions to Reduce Risks from Induced Seismicity (Lead: Mutz)

The increase in seismic activity near oil and gas fields, as well as public discussion of these activities, has gradually transformed initial skepticism by industry and regulators of any connection between earthquakes and oil and gas development activities to recognition that additional research and, perhaps, regulatory action may be needed [129]. Three states with increased seismic activity (OH, OK, and TX) have initiated or completed rulemaking processes to modify regulation of wastewater disposal wells to address immediate concerns. In Colorado, operators are required to define, prior to permit approval, the seismicity potential and proximity to faults of a proposed wastewater injection well. Under the auspices of the State Oil and Gas Regulatory Exchange of the States First Initiative, these states and several others have initiated the Induced Seismicity by Injection Work Group (the IS Work Group) to proactively discuss the possible association between earthquakes and injection of waste fluids [130]. At the same time, communities, legislators, and regulators are struggling to find and assess the facts to develop regulations that balance safety and environmental protection [131,132] with additional regulation.

Research Questions: *(i) What are the current laws and regulations for eliminating or minimizing induced seismicity associated with oil and gas development and for mitigating the influence of injection-induced events on communities and the environment?*

(ii) What are the characteristics of a model regulation that could serve as a guide for states and

others dealing with induced seismicity issues?

Research Approach*:* These questions will be addressed through the creation of a searchable catalog of laws and regulations related to induced seismicity. This catalog will be stored as a publicly accessible, internet-based database on the Public Health Law Research project's Law Atlas platform at http://lawatlas.org/oilandgas. This platform currently catalogs water quality and water quantity regulations for oil and gas development, developed by Mutz' team at the CU Law School. At a minimum, the catalog will include regulations addressing: constitutional and statutory authority for jurisdictions to regulate in these areas; permitting of disposal wells; technological requirements to prevent induced earthquakes; monitoring and reporting requirements; authority of agencies to take actions in response to events, including to modify, suspend or terminate a permit to operate or to require more information (*e.g.,* fault mapping) for decision-making; provisions for public notification and participation; damage compensation; and compliance and enforcement provisions. In the context of regulations associated with permitting, the team will examine: general requirements for permit application information; special requirements for permit application information in higher risk areas; criteria for determining risk types and thresholds and limitations on applicability of regulations.

Early in the first year of the project, the regulatory team will finalize the list of regulatory topics and identify specific provisions of interest in the context of wastewater injection associated with oil and gas development. For this effort the team will review selected proposed regulations and comments/testimony published in state and federal rulemaking processes regarding wastewater injection wells; identify induced seismicity regulations for other types of developments or activities*, e.g.,* geothermal development, mining, water impoundments, and ground water extraction; and identify seismicity regulations for oil and gas production activities. Although other aspects of this proposal focus mainly on induced seismicity from wastewater injection wells, review of seismicity regulations for a larger set of development activities will provide a broader perspective for identifying appropriate provisions of a model regulation (Research Question ii). The regulatory team will identify provisions of state and federal regulation through use of legal databases (*e.g.,* Westlaw or Lexis), searches of the regulatory agency rules, and in consultation with the project's External Advisory Board and others working on oil and gas seismicity issues. At a minimum, data collections will address Colorado, Texas and the other 11 states currently included in the LawAtlas database. These states are home to the major unconventional oil and gas development areas throughout the country. Throughout the period of the grant, the regulatory team will update the database with regulatory revisions for the initial set of states and add states as new seismic-related rulemakings occur. The LawAtlas catalog of regulations, along with background materials on injection induced seismicity and a factsheet comparing regulations among the states will be disseminated through websites hosted by CU, and partners in oil and gas research as described in the management and integration plan. The catalog will be a resource to other members of the project team in identifying issues of interest to the public, and both the regulatory and regulated communities.

Existing and proposed regulations, as well as knowledge obtained from this study from seismic monitoring, engineering risk assessments and stakeholder interviews will be used to propose and investigate a model regulation. These evaluations will utilize the catalog and input from the CCIS research team, advisors, regulators and industry to investigate: 1) geographic variability among existing regulations, 2) the role scientific investigations are playing in development of new regulations, 3) the applicability of wastewater injection regulations for hydraulically fractured production wells, 4) costs of enforcement and costs of compliance, 5) and appropriate jurisdictional levels for regulation. These analyses will inform a white paper describing the proposed model regulation. The regulatory team will coordinate its work on the LawAtlas catalog, model regulations, and white paper with the IS Work Group. Geoscience modeling and monitoring studies (Theme I), engineering risk analyses (Theme II), and social science (Theme III) will be used to re-evaluate the model regulation in the context of new data.

4. EDUCATION AND OUTREACH PLAN

4.1 Education and Training

CCIS will train a cohort of interdisciplinary scholars to be future leaders in the creation, management and maintenance of a sustainable energy infrastructure. These future practitioners include undergraduate students, graduate students, postdoctoral scholars and a legal fellow, all of whom will play a central role in achieving the objectives of the research plan. Students and faculty will be expected to participate in regular cross-disciplinary research meetings. In addition, faculty will mentor students about the challenges and opportunities of interdisciplinary work and encourage team building. To begin, CCIS will host a two-day training session in which each faculty member will train the student cohort on the research methods, including seismic monitoring and instrumentation, qualitative and quantitate data analysis methods, and modeling approaches. CU is a leader in academic initiatives focusing on sustainability, and students will also participate in two other activities: 1) a campus-wide colloquia series on successful strategies for interdisciplinary scholarship, and 2) campus-wide education initiatives in sustainability, such as courses offered through the Renewable and Sustainable Energy Institute.

CCIS will also develop and co-teach a one-of-a-kind interdisciplinary course on induced seismicity. Because of the complexity of the physical, engineering, social and regulatory processes, the course will address induced seismicity from a variety of perspectives, including: 1) mechanics of earthquake generation, 2) systems approaches, and 3) seismological and community-based field research. Class sessions will be co-taught, such that each class period considers multiple disciplinary perspectives. Research shows that interdisciplinary courses can be successful in promoting integration of ideas for sustainability [133]. Students will be surveyed to evaluate the attainment of course learning objectives, receptiveness to interdisciplinary thinking, and knowledge gained on sustainability concepts by modifying existing instruments [134–136].

Recruitment of students from diverse backgrounds is of the utmost importance. All faculty members on the CCIS team have a proven track record in recruiting and retaining underrepresented students, and both Liel and Javernick-Will have published articles on this topic [137,138]. The faculty, which are (unusually) majority women, are well-positioned to mentor female and other minority students, which has been shown to contribute to success and retention of underrepresented students (*e.g.* [139]). Moreover, NSF-supported research by Javernick-Will [138], among others, have suggested that engineering and science oriented toward making a difference and effecting change, like that pursued here, can be persuasive for engaging students with different backgrounds.

4.2 Outreach and Technology Transfer

Our extensive plans for outreach and technology transfer, included the composition of a committed External Advisory Board, are described in detail in the Management and Integration Plan.

5. RESULTS OF PRIOR NSF SUPPORT

Liel, A: #1250163, 6/13-5/18, $400k , *CAREER: A Multi-scale Methodology for Assessing the Reductions in Seismic Risk Possible through Building Retrofit Design and Policy.* Results: *Intellectual Merit*: Quantified spatial correlations in building seismic response and losses; Developed and evaluated new procedures for regional seismic loss estimation; Created database of seismic retrofit ordinances for evaluating policy effectiveness. *Broader Impacts*: 2 Ph.D., 3 M.S & 1 B.S. students worked on the project, including 2 women. Products: 1 conf. proc [140], 1 journal articles [141], 1 article in review.

Sheehan, A: #0843657, 5/09-5/12 + NCE, $654k, *Collaborative Research: Formation of Basement-involved Foreland Arches: An Integrated EarthScope Experiment.* Results: *Intellectual Merit*: Ran combined active-passive seismic experiment in WY, determined detailed basin and Moho geometry from seismic wave, recorded local earthquakes, developed methods for use of teleseismic recordings on geophones. *Broader Impacts*: 3 Ph.D & 7 undergraduate students worked on the project. Products: 4 open data sets at IRIS, 4 journal articles to date [55,142–144].

Ritchie, L: #1248118, 2/13-1/15, $199,993: *Mitigating Litigating: NSF RAPID Research to Study Social and Psychological Impacts of the 2012 BP Claims Settlement*. Results: *Intellectual Merit:* Collected household survey data examining how settlement and litigation processes form the BP *Deepwater Horizon* disaster influence social / psychological recovery for comparison with communities affected by the *Exxon Valdez. Broader Impacts:* Will increase knowledge of how processes of litigation and damage claims settlements can facilitate or hinder community recovery. Products: none yet.