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Current State of Knowledge Regarding the Risk of Induced Seismicity at CO_2 Storage Projects

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The Current State of Knowledge Regarding the Risk of Induced Seismicity at CO_2 Storage Projects

Key Messages

- Investigation into the link between induced seismicity and very large-scale waste water disposal has advanced significantly since the 2013 IEAGHG review of induced seismicity. Seismic monitoring of CO_2 storage sites has also led to a better understanding of the phenomenon especially the propagation of microseismic events.

- The use of sophisticated monitoring techniques has been refined and enabled enhanced event location and improved model calibration. Evidence from microseismic detection techniques at demonstration CO_2 storage sites has also revealed temporal correlations with periods of high injection rate and bottom-hole pressure. There is no evidence of felt seismicity at any of the 36 CO_2 storage sites reviewed in this study with the exception of one CO2-EOR (enhanced oil recovery) site.

- Monitoring microseismicity at CO_2 storage sites has revealed events are more common during perturbations in flow, including shutdowns, than they are during injection.

- The analysis of geomechanical responses in reservoirs can contribute to the assessment of the risk of felt seismicity caused by pressure perturbations within a project area. Geomechanical modelling is therefore of critical importance and requires verification with measured parameters.

- Large-scale waste water disposal has a clear association with induced seismicity across some regions of the south - central US. However, it is important to recognize that natural pre-existing tectonic stresses can be triggered by pressure changes induced by fluid injection. Some regions of the US, such as North Dakota near the Canadian border, and in the northeast US, exhibit a relative lack of felt seismicity, despite waste water disposal.

- Historical evidence, that predates large-scale waste water disposal, also shows that natural tectonic activity has been responsible for seismicity across the south – central and other regions of the US.

- Waste-water disposal intervals at a depth of ~2km, for example in Oklahoma, can have related seismic hypocenters at an estimated depth of ~5km in the crystalline basement.

- Other factors can complicate when seismic events might occur. Stress can be transferred to deeper fault zones that are critically stressed and susceptible to slip. This mechanism may have been responsible for the Castor event off the north-east coast of Spain. Earthquake to earthquake interaction is also possible where accumulated stress from previously seismically non-active regions can be affected.

- In response to concerns associated with induced seismicity in the US a series of precautionary operational measures were introduced. These have included mandatory injection into higher stratigraphic formations, significant volumetric reductions in waste water injection or, in some cases, complete cessation and a ban on new disposal wells in close proximity to known regional faults. Seismic monitoring plans also need to be implemented and include tests to detect the presence of faults. Specific regulations depend on each state.

- Regulatory authorities have defined rules and expectations for permits, incorporating in most cases, past earthquake data (distance of seismicity from the well and magnitude of events) and characterization of subsurface hazards. In some cases (Canada, Oklahoma, Ohio, UK), the operator has to follow a traffic light system that "controls" its actions and provides guidance on risk mitigation based on an earthquake magnitude threshold. This depends on each country or state.

- Causes of seismicity at specific locations need to be clearly explained especially to local communities that may be affected by CO_2 storage sites. For example, in Japan natural seismicity is a regular occurrence, and felt events are not uncommon, consequently the origin of such events needs to be conveyed so that they cannot be associated with a CO_2 storage site. In another example, and in contrast, geothermal energy produced from the Geysers field is actively monitored because of the link between the field's operations and induced seismicity. Successful proactive outreach policies at the Tomakomai CO_2 storage demonstration site in Japan, and the Geysers geothermal field in California, have demonstrated how seismic origin, and its potential impacts, can be effectively communicated.

Background to the Study

Induced seismicity is a well-known phenomenon and has been associated with a number of subsurface activities including, mining, geothermal energy, waste water disposal and, more recently CO_2 storage.

The IEAGHG programme has previously investigated induced seismicity in a study published in 2013[i]. This study reviewed the causes of induced seismicity and the dominant mechanisms that cause the phenomenon to occur. The study highlighted the dependency of models used to predict induced seismicity on the quality of the input data, including knowledge of the orientation and magnitude of the local stress field; whether any local fault networks were present and whether they could be affected by a pressure front. The hydraulic properties of the formation or fault zone medium, such as permeability, diffusivity, and the elastic properties of the medium, such as elastic moduli and thermal expansion coefficients are also important inputs. The study included case studies taken from oil production and stimulation, hydrothermal and enhanced geothermal systems and waste fluid disposal. The long-held view that there is a relationship between fluid injection and induced seismicity was reinforced by the research. The 2013 study concluded that the relationship of the origins of induced seismicity in other industries affected by the phenomenon is not necessarily comparable to large-scale CO_2 storage.

Since the 2013 review there has been further widespread reporting of induced seismicity in a number of subsurface applications. In some cases events were felt at the surface. There have even been damaging earthquakes with magnitudes larger than five on the Gutenberg-Richter scale, particularly linked to waste water disposal in the USA[ii,iii,iv], and a triggered large event at Pohang, South Korea associated with an Engineered Geothermal Site site[v]. Most waste water disposal is associated with onshore oil and gas production, or in some instances spent fluid from fracking operations. It is important to recognise the scale of waste water disposal and its relationship with seismic events. There are approximately 35,000 active waste-water disposal wells, and there are well over 1,000 disposal wells that inject 100,000 bbls/month (15.9m l/month). Only a few dozen of these wells are known to have induced felt earthquakes. The concerns raised from waste water disposal have led to proactive initiatives, such as the TexNet[vi], to monitor seismicity and determine its relationship to waste water injection and other causes including naturally occurring seismicity.

Large-scale CO_2 storage has also continued to provide new data on induced seismicity due to active monitoring during CO_2 injection using a combination of surface and wellbore sensors. This wealth of data has generated new insights and a better understanding of how fluid injection relates to seismicity. Before injection begins, baseline seismic monitoring has been able to establish the relative proximity of seismic events unrelated to CO_2 injection[vii]. Observations, for example at the Illinois Basin Decatur Project (IBDP) site during and after injection, have enabled researchers to identify distinct linear clusters which have increased in distance from the injection well over time. By using sophisticated monitoring techniques event location has been refined and used to improve model calibration[viii].

Other notable onshore, and near-shore, CO_2 storage demonstration sites have actively monitored induced seismicity which can provide valuable insights. These include Aquistore, Tomakomai, Weyburn, In Salah and Quest.

With new and more abundant data on induced seismicity becoming available, it is important to be able to draw distinctions and similarities between different CO_2 storage sites based on site-specific characteristics. Clear distinctions need to be made between CO_2 storage operations and other industrial disposal operations, particularly waste-water disposal. The magnitude and impact of significant volumes of waste-water disposal, especially when there is no association with CO_2 storage, needs to be placed in context.

Project scope

The primary objective of this study is to summarize the levels of induced seismicity observed in or near CO_2 storage sites, and the consequences of the induced seismicity in terms of impact on people, as well as the environment, assets and reputation of operators, authorities, and on CCS technology.

A second objective is to gain an understanding on processes that industry and authorities employ to manage the risk of induced seismicity.

A third objective is to present notable case studies where outreach measures have supported operators and regulators in managing concerns of stakeholders in connection with induced seismicity.

The final task of the study is to identify current research and innovation trends to better manage the risk of induced seismicity.

Findings of the Study

A total of 36 current CO_2 storage sites that are either actively or have previously monitored CO_2 injection were selected in the study. This sample was subdivided into associated operation (enhanced oil recovery (EOR) (15), saline aquifer storage (15), depleted oil and gas (DO&G) (4) or mixed EOR and saline storage (2)). Desirable data such as pressure elevation, and any metrics of the state of stress, were not available for many of the projects in a form that could be easily compiled. In additional about 100 projects, mostly in the US, injected CO_2 for commercial EOR, but do not have to provide monitoring data other than mechanical integrity and injection data required by state regulators. Seismic and microseismic monitoring has not been required for EOR projects by US state regulators. Investigations conducted with selected EOR operators revealed that field specific data on seismicity are not normally collected as part of most EOR operations. However, within Texas, there is no evidence from clusters of seismic signals detected from regional seismic arrays, or from EOR operations, of any localised felt seismicity with the exception of Cogdell Field.

Of the 36 projects surveyed in this study 12 did not undertake seismic monitoring. Most of these projects (10) are EOR operations. The other two are CO_2 saline storage sites. Of the population of 19 projects that undertook any type of seismicity monitoring, 15 are EOR operations, four projects inject CO_2 into depleted gas fields, 15 projects use saline aquifer storage, and two projects are mixed EOR and saline aquifer storage. Seven projects have ceased injection and the rest are ongoing, however the level of monitoring is variable, the maximum reported injection amount is >70 million tonnes at the SACROC EOR project, which has been injecting an average of >2 million tonnes of CO_2 per year. The SACROC field was not monitored for microseismicity in reported studies, however, no detections are flagged in detailed regional studies, as compared to the nearby Cogdell Field which was seismically active.

Of the 19 projects that undertook seismic monitoring, 10 detected some microseismic signal attributed to injection (two in DO&G (depleted oil and gas), three in EOR and five in saline). Nine detected no signal that could be reliably attributed to injection. Two saline storage sites, Nagaoka and Tomakomai, in Japan, detected nearby major felt earthquakes. Analysis conducted by the research teams showed that these events were unrelated to injection. Only one site, Cogdell (EOR), experienced seismicity that was reported as felt. Informal reports indicate that the operator made some adjustment to the injection and production rates, however detailed data or analysis are not publicly available. Additional investigation of this EOR project, which is associated with significant seismicity, is warranted to gain a better understanding of its causes.

In a number of EOR and storage projects, detection and analysis of microseismic (M_W<1) events have helped to improve the understanding of flow processes in the subsurface. The analysis of geomechanical responses in reservoirs can be used to assess the risk of felt seismicity caused by pressure perturbations within the project area. Understanding the mechanism that could cause a felt event can help to minimize this risk.

The In Salah CCS project in Algeria, which was run between 2004 and 2011, is an important case study because the geomechanics of the site were well documented. However, seismicity itself was not an issue as magnitudes remained M_W <1. At the In Salah gas processing plant location near the Krechba Field, in central Algeria, 3.8 million tonnes of CO_2 were injected into the downdip water leg at a depth of about 1.9 km into the same 20 m-thick Carboniferous sandstone that produces gas on the crest of the structure. Three horizontal injection wells perpendicular to the regional fracture patterns were used for injection because the matrix permeability of the injection unit is low (1 mD). Microseismic monitoring was conducted using a single 48 level 3-component geophone string at 30 to 500 m depths in a well. Unfortunately there were various equipment malfunctions during injection which limited the detection of the hypocenter location. However, monitoring did show temporal correlations with periods of high injection rate and high bottom-hole pressure.

The Archer Daniels Midland (ADM) ethanol plant in Decatur, Illinois is another prominent demonstration site. Here CO_2 is being injected into the basal Cambrian Mount Simon Sandstone. Sensitive seismic monitoring during previous and the current CCS projects has added substantial knowledge on microseismicity during storage operations.

The aim of the initial project, started in 2001, was to inject just less than the permitted amount of CO_2 (1 million tonnes) over three years into several zones of the regionally extensive sandstones of the Mount Simon Formation. This geological unit is a regionally important target for CO_2 storage. The project permit stated that ADM was required to conduct continuous performance of passive seismic monitoring using a combination of borehole and surface seismic stations to detect local events over M_W 1.0 within the Area of review (AoR). The Mount Simon Sandstone is 450 m thick in the project area, and overlies the think and low permeability pre-Mount Simon sandstone and the Precambrian basement. The reservoir, underlying rocks, as well as overlying confining zones were cored and an extensive monitoring system was developed.

The injection well was perforated at depths of 2,128 - 2,149 m and the well was instrumented with geophones at 1,750 m and 1,870 m. Eighteen months of pre-injection baseline data were collected from this array. A separate monitoring well, with a dedicated five-level geophone array at depths 1,875 - 2,118 m, was installed after the initial seismic events were detected to improve monitoring. In addition, a study by the USGS detected 3,400 microseismic events ranged from M_L 07 to 1.52 that were located in the injection period. Events have been located in the low permeability zone in the lower Mount Simon sandstone, Pre-Mount Simon formation, and the Precambrian basement. Modelling indicates that the microseismicity is associated with evolution of the pressure field, not the CO_2 plume itself, and events are more common during perturbations in flow, including shutdowns, than they are during steady operation. The ADM site passive seismic monitoring is a combination of borehole and surface seismic stations deployed to detect local events over M_L 1.0 within the Area of Review (AoR). The ADM project has showed a relationship between injection cycles and seismicity specifically the location and temporal occurrence of microseismic events (M_L 0 – 2). This is a significant observation for future CCS project developments. The injection interval was moved to a shallower zone to reduce the pressure communication with the basement as a precautionary measure.

The association between induced seismicity, especially felt events, and waste water injection has been known for several decades. The phenomenon was suspected following the M_W 5.2 earthquake in 1962 that was linked to the Rocky Mountain Arsenal sites. There have been a series of seismic events across many areas of the south-central section of the US especially in Oklahoma, Arkansas, Texas and New Mexico. An inventory of many events from water injection and geothermal activities has been previously applied and now extended to CCS.

The experience from waste water injection can be directly translated to guidance for large scale CO_2 injection operations. Although CO_2 is a more compressible fluid than water, the effect on pore pressure is the same as water. At many sites, a large proportion of the area of the pressure plume associated with CO_2 injection is in the water phase. This is distinct and much larger than the CO_2 plume, but is identical to water injection cases.

Induced seismicity is also associated with the widespread use of hydraulic fracturing attributed to oil and gas production as well as waste water disposal. These practices have raised public concerns. The Barnett play in Texas, which is the target formation, was the first beneficiary of this technique. The combination of high-volume hydraulic fracturing technology and horizontal drilling took off in 2005. Some of the earliest earthquakes then occurred in 2008 in the Fort Worth Basin of north-central Texas. The Dallas - Fort Worth (DFW) International Airport earthquake sequence of October – November 2008 marked the beginning of an ongoing series of seismic events including 10 felt earthquakes (range from M_W 2.6 to 3.3). The sequence was interpreted by some, but not all, as the result of produced water disposal into two salt water disposal wells (SWD) located on the DFW airport. The events alarmed local residents and the State of Texas initiated a review of its regulations that is still ongoing.

Following this initial sequence, seismic events related to high volumes of water disposal were observed elsewhere in the Fort Worth Basin (M_W 4.0 2015 Venus sequence). Seismic events have occurred in other hydrocarbon rich shale plays in Texas, and in other oil and gas producing states, in particular, a M_W 4.0 earthquake in December 2011 in Youngstown, Ohio, the <M3$_W$ Greenbrier cluster (2009-2010) and the M_W 4.7 Guy-Greenbrier swarm in 2010-2011 in Arkansas, and the M_W 5.7 earthquake in November 2011 near Prague in central Oklahoma. In addition to these relatively high magnitude earthquakes, thousands of earthquakes were potentially felt (~>M_W 3) and tens of thousands were observed (>M_W 1.5-3). It should be noted, however, that some areas in the mid continental US, east of the Rocky Mountains, have a history of natural tectonic earthquakes (Rio Grande rift in New Mexico and West Texas; mid-continent rift, and the New Madrid seismic zone beneath the Mississippi valley near the confluence of the Mississippi and Ohio Rivers). In addition, all states have the potential for human-induced seismic events not related to salt water disposal (SWD) and due to oil production, groundwater withdrawal or dam building. Although, in the statistical sense, recent seismic events are correlated with SWD wells and pressure build-up, some events might be natural.

The south-central section of the US (New Mexico, Texas, Oklahoma, Kansas, Arkansas) seems particularly affected by numerous and sometimes large seismic events. However, the link between the spatial distribution of these events and their possible cause is not clear cut. The stacked plays (intervals at multiple depths) of the Permian Basin in west Texas and southeast New Mexico are characterized by a high water cut. Most used water disposal intervals are located at shallower depths than the production intervals. This, however, does not prevent earthquakes from striking the region, for example, the M4.6 Mentone earthquake in March 2020 in the Delaware sub-basin of the Permian Basin of West Texas. Further east in Oklahoma, Kansas and Arkansas waste produced water was injected into karsted marine carbonates (cavernous and locally dissolved limestones and dolostones) of the Arbuckle Group, a formation that directly overlies the Proterozoic crystalline basement. Although disposal intervals are at a depth of ~2km, seismic hypocentres are estimated to be at 5km and within the basement. Several researchers have postulated that this is the result of the combination of the nature of the plays with a relatively high-water production and of the position of the disposal intervals directly overlying the Proterozoic crystalline basement. This observation has driven most of the early regulatory responses to the increased seismicity. Operators were redirected to disposal sites well above the Precambrian basement. In contrast other regions of the United States, such as the Bakken formations in North Dakota near the Canadian border, and the Marcellus Shale in the northeast US, display smaller produced water volumes and a relative lack of felt seismicity.

New Best Practices developed in US in response to induced seismicity

With a sharp increase in seismicity associated with waste water disposal a number of US states have implemented measures aimed at limiting the impact of the phenomenon. The measures include an increase in seismometer density to augment the USGS (United States Geological Survey) network. Although an increased instrument density improves the accuracy of detecting earthquake epicentres, the hypocentres are difficult to determine accurately because of a lack of velocity models. The use of pressure monitoring in deep saline water disposal wells is another option but it is rarely implemented. The State of Oklahoma did deploy a pressure monitoring system, however, the approach has a limitation. Very small pressure increases can trigger seismic activity on a pre-stressed fault, so reliance on pressure monitoring alone may not be effective.

The concerns in Oklahoma led to technical restrictions and a warning system. Injection rates were cut to 10-15,000 barrels per day (bpd) (1,589,873 – 2,384,809 l/day) per well. Consequently injection fell from 90m bbl/month to 30m bbl/month (14,309m – 4,777m l/month). A mandatory plug back of the basement section on injection wells hundreds of feet above the basement unconformity with the Precambrian basement was also instigated. In addition, the state introduced a traffic light system. If a >M_W 3.5 event occurred within a 1.25 mile (2.0 km) radius injection has to be suspended and a moratorium on injection within a 7 mile (~11.3 km) radius is implemented. In addition, any SWD (saltwater disposal) well within 3 miles (~4.8 km) of a known fault, or >M_W 2.0 seismic activity, requires seismic monitoring.

In the neighboring state of Arkansas three wells nearest to a M_W 4.7 event in vicinity of Guy-Greenbrier area had to be shut down and later plugged and abandoned. There was a moratorium on new disposal wells and seven existing wells had to report injection rates on an hourly basis. Restrictions were also imposed on SWD wells including a ban on new SWD wells within 1 mile (1.6 km) of known regional faults and 5 miles (~8.0 km) from a deep fault extending from basement. SWD wells must be spaced from 0.5 – 5 miles (~0.8 - 8.0 km) apart depending on whether injection is within a stratigraphic interval above or below the target Fayetteville Shale. A seismic monitoring plan must be submitted and include tests to detect the presence of faults.

In Texas, Barnett Shale operators have been encouraged to switch to the Ellenburger Formation as a preferred disposal option. Additional scrutiny is now required on future well applications such as fault mapping. However, unknown faults can be discovered by seismic events.

Despite some initial skepticism linking seismicity and waste water disposal, regulators and operators currently follow a pragmatic approach in many US states. The revised approach integrates current scientific knowledge of induced seismicity and the threshold levels that equate to public sensitivity of the impact of felt seismic events.

A regional response to limit potential induced seismicity linked to waste water disposal has now emerged. In Oklahoma injected volumes have been decreased whereas in New Mexico injection next to critically stressed faults is limited. Some states also pursue more innovative ways to limit injection volumes such as recycling produced water. This practice is spreading among operators with various levels of enthusiasm, from almost no recycling to being a strategic priority. However, the overall recycled volume remains a small fraction of the total volume of produced water. Regional impacts also need regional monitoring and control solutions.

There are factors that complicate the predictability of seismicity. Stress can be transferred to deeper zones that are prone to be critically stressed and susceptible to slip. Also, an earthquake to earthquake interaction is also possible where accumulated stress from previously seismically non-active regions can be affected.

The state of stress in the crust can be assessed using different approaches (geodetic, InSAR, borehole breakouts, bottom hole and even wellhead pressures, seismicity monitoring, etc.). However, there are limitations in the ability of these techniques to provide information with sufficient accuracy in a short timescale. Consequently it can be difficult to directly associate seismic data to a current state of stress.

With limited or no pre-injection characterization, collecting data to affirm or modify characterization assumptions is required. If the site is close to an active tectonic zone it is possible that seismicity information could be available. This could include (spatio-temporal distribution, fault plane solutions, waveform cross correlation relative to relocation), along with accurate fault information (from passive seismic receivers). Such data can be used to identify active rupture zones and the maximum horizontal stress direction (SHmax). If seismic data are absent in the area of interest, and in the absence of an existing seismic array, the deployment of a local array is preferable in order to identify any low magnitude seismicity ($M_W \leq 1.0$).

There is some evidence that with sufficient monitoring and identification of spatial clusters it is possible to attribute seismicity to specific operations like hydraulic fracturing and salt water disposal using statistical analysis.

Induced Seismicity and Forecasting

Methods for seismicity forecasting are broadly divided into physical process models and seismicity-based forecasting models. Seismic hazard models can be used to forecast earthquake hazard and damage intensity for a given year. The model is based on seismic events recorded over a specific time interval and the presence of known faults. Seismic events are then categorized as either induced or natural, the rate at which these events occur and their duration. Maximum magnitudes can be applied and alternative ground motion models can also be used.

A physics-based forecasting model has been applied to predict seismically induced hazards in Oklahoma and Kansas. The model forecasts the probability of damaging earthquakes in time and space by using a hybrid physical-statistical model. In this model the seismicity is driven by the rate of injection-induced pressure increases at any given location. Spatial variations in the number and stress state of pre-existing basement faults caused by these pressure increases is factored into the model. A three-dimensional hydrogeological model was developed to simulate fluid injection from wells operating in a specific area for 20 years. The model was then used to compute the probability of triggering M>3 earthquakes from the distribution of pressure induced events and monthly pressure rates at seed points in the model. Using this model 1-year maps of the seismic hazard were generated to assess the probability of potentially damaging induced earthquakes.

Models have been used to establish a link between seismological observations and the geomechanical properties of the region of interest by observing the relationship between the critical stress state, the cumulative number of events and earthquake magnitude. Geomechanical modelling is, therefore, of high importance for large-scale geological storage sites. The approach requires the integration of key physical properties including critical stress, formation fracture pressure limits, fault slip potential and porosity. These parameters need to be used with measured data including injection volumes, pressure rates, seismic moment and Coulomb stress. Pore pressure and stress changes for an earthquake cluster can then be computed and sensitivities of the model parameters established.

Bayesian statistical methods can be used to evaluate seismic hazards based on the magnitude of the largest expected seismic event over a future time interval. Bayesian statistical methods provide a suite of approaches to analyse statistical aspects of seismicity and then predict distributions of seismicity based on past seismic distributions.

A relative intensity forecast model can be used to predict the total number and frequency-magnitude distribution of future seismicity. The model monitors seismicity in real time with multiple statistical forecast models. The probabilities of exceeding a ground motion intensity level can then be translated to forecast the level of a seismic hazard. This modelling approach can be used by operators to control injection rates so that they do not exceed thresholds that could lead to induced seismicity of sufficient magnitude to cause concern. Based on the Omori-Utsu law of aftershock decay and the Gutenberg-Richter law of frequency-magnitude distribution, seismic hazards can be forecast based on seismicity catalogs.

Seismic Hazard and Public Perception

Public perception ranks induced seismicity as a frequent and consequential concern connected with the implementation of CCS. In a metadata review of 135 public perception studies on CCS, induced seismicity is ranked in the top four concerns and comparable to leakage risk and CCS effectiveness. Concerns about seismicity have caused a number of jurisdictions globally to put a moratorium on injection, with a motivation to stop hydraulic fracturing but this attitude also has a derivative impact on CCS. However, usually, infrastructure used in CCS projects is unlikely to be affected and the likelihood of damage is minimal for a given small to moderate ground motion.

Permitting and Regulatory Oversight

In areas of increased injection induced seismicity, regulatory authorities have often defined rules and expectations for permitting, incorporating in most cases, past earthquake data (distance of seismicity from the well and magnitude of events) and characterization of subsurface hazards. In some cases (Canada, Oklahoma, Ohio, UK), the operator has to follow a traffic light system that controls its actions and provides guidance on risk mitigation based on an earthquake magnitude threshold, which are, in most cases, different for each country or state.

Proactive outreach policies at two different locations have demonstrated how seismic risk, and its potential impacts, can be effectively communicated.

The Tomakomai CCS Demonstration Project was conducted with the understanding and support of the local government, industries and local community. Its permit included a commitment to provide a comprehensive outreach programme to explain the project and a series of monitoring activities. These included:

- Panel exhibitions held in Tomakomai and nearby cities, as well as other cities in Japan.
- CCS forum held annually for Tomakomai citizens since 2011; typical attendance ranging from 300 to 400 people.
- Site tours of facilities and observation wells are open to the general public.
- Information disclosure system: disclosure of CO_2 injection volume, borehole pressure and temperature, seawater CO_2 concentration, earthquake and micro-seismicity data on a Japanese CCS website.
- Mini seminars for students held in universities in Hokkaido as well as nationwide.
- Kids lab classes in primary and secondary schools in Tomakomai to enhance their understanding of global warming and CCS through CO_2 experiments. Site tours for children are also included.

Another example of strengthening the engagement with the public and the outreach activities is the Geysers geothermal field. The operator developed the Calpine Geothermal Visitor Center in Middletown, California in 2001. This visitor centre consists of displays presenting the history and geology of the Geysers. It also provides interactive displays designed to educate the visitors about key issues and benefits of geothermal energy. In addition, exhibits have been created to examine sustainable energy options and present the challenges and the potential of enhanced geothermal systems (EGS). The exhibition provides videos and displays which highlight the key components of drilling technologies.

Differences Between CO_2 Storage and other Technologies Associated with Induced Seismicity

It is clear from this review, and many previous investigations, that induced seismicity can be caused by many different types of subsurface operations. Consequently the factors that cause the phenomenon need to be clearly distinguished for each specific technology where there is a link. Operator practice at individual sites is also important because it demonstrates a commitment to manage and monitor a site and take appropriate action to minimise any potential adverse impacts caused by induced seismicity. In contrast to natural gas storage, oil and natural gas extraction and geothermal energy, CO_2 storage into deep saline formations, and depleted oil and gas fields, requires controlled injection into a permeable formation. The permanency and the evolution of the pressure regime in a CO_2 storage site is dissimilar to gas storage where there is cyclical loading and gas extraction where there is pressure depletion. Fluid injection and pressure fluctuation in geothermal reservoirs, which are known to cause induced seismicity, are designed to optimise heat energy under quite different conditions to those experienced in CO_2 storage sites. CO_2 storage is conducted under carefully controlled conditions to ensure formation pressure does not exceed fracture pressure limits or the critical stress limit of faults.

Other forms of subsurface operation in the oil and gas industry, especially hydraulic fracturing, are also quite different and should not be confused with CO_2 storage. It is important, however, to make a clear distinction between CO_2 linked to EOR and CO_2 storage into deep saline formations or depleted oil and gas fields. The former is a technical operation to extract oil, although some CO_2 will be permanently retained. There is evidence from this, and other studies, that CO_2-EOR can cause induced seismicity. At least one felt event has been associated with a CO_2-EOR operation in Texas.

It is also imperative to differentiate between induced seismicity associated with waste-water disposal in the oil and gas industry and CO_2 storage into deep saline formations or depleted oil and gas fields. Disposal of waste water (formation brine) produced from active oil and gas fields is widespread and, in North America, re-injection into producing reservoirs or injection into different formations is commonplace. This practice has been linked to induced seismicity because of pressure changes and reactivation of faults. Unlike like oil and gas production, which is optimised for hydrocarbon extraction, the management of a CO_2 storage formation, and any associated formation used for brine disposal, would be engineered for large-scale CO_2 injection possibly over decades. The suitability of the storage site therefore requires reservoir and seal formation characterisation as well as characterization of other geological features including faults which may present seismicity risks. The site appraisal will also depend on modelling to ascertain capacity estimates, CO_2 migration behaviour and pressure plume extent. Geomechanical changes and any associated induced seismicity risk will form an integral part of this site characterisation. Although the techniques used in subsurface geological investigations are very similar to those used in oil and gas exploration and production the objectives are quite different and not directly comparable. CO_2 injection into a storage formation can lead to an increase in pressure which may require brine extraction as a pressure control measure. However, this practice depends on the lateral extent of the storage formation and whether it is in hydraulic communication with a regional aquifer which allows pressure dissipation. Factors such as multiple injection sites, and the rate of injection, may require brine extraction and re-injection into different formations depending on location and disposal options.

As a comparatively new technology the development of CO_2 storage requires background data acquisition on geological conditions. These will need to include overburden characterisation as well as the target storage and seal formations and structural features such as faults. Proximity of proposed injection intervals to crystalline basement will also require careful scrutiny. As with other industries CCS, and especially the storage element, benefits from the expertise and technology advances made in the oil and gas sector and geothermal energy plus a better understanding of the causes of induce seismicity.

Expert Review Comments

- Improvements to the terminology used to describe induced seismicity and micro seismicity and felt seismicity. A table explaining the magnitude of seismic events has been included.
- The report requires a recommendations chapter at the end that pulls together the important lessons that can be drawn from the injection induced cases and the management of large volumes of waste water injection management. These should cover monitoring, site selection, pressure management, outreach measures – both included
- Heavy US focus, but the report does includes some mention of European experience and regulations. The US and Canada have experienced very large volumes of waste-water injection not experienced in onshore Europe.
- Inclusion of the Castor event off the north-east coast of Spain and its significance. The event is an example of induced seismicity thought to have been caused by stress transferred to deeper a fault zone that was critically stressed and susceptible to slip.
- The CO_2-injection at Codgell was associated with 18 M>3 events and a Mw 4.4 event in 2011. This should be noted and is highlighted in the report.
- In the vicinity of the Sleipner field (1 km distance) a M3.5 event was observed, which could be associated with the field (the location errors in this part of the North Sea are very large). This should be noted and is explained in the report

Conclusions

- About half of the CO_2 injection projects report monitoring for seismic activity. None have had seismic events that were problematic for operations and the continuation of the project. In some cases, high quality measurements of low magnitude events and modelling has helped to understand the evolution of the pressure field related to the flood operations. In other cases, events have been small and sparse, and build confidence that seismicity is less likely to be a major risk in the project area.

- For water injection projects associated with oil and gas production, high volume water injection both for hydraulic stimulation to inducing fracturing in low permeability formations, and for subsurface disposal of large volumes of produced brine, has caused felt seismic events in some areas where hydraulic stimulation was applied. Regulatory authorities in some US states have responded to this pattern of induced seismicity by imposing conditions on disposal operations including injection into sedimentary formations that are not immediately above crystalline basement. Disposal rates have also been cut by two-thirds and traffic light protocols introduced which can impose suspension of injection if detected events exceed a specific threshold.

- Seismicity information (spatio-temporal distribution, fault plane solutions, waveform cross correlation relative relocation), along with accurate fault information (from seismic responses), are the key parameters to determine conditions that might cause induced seismicity.
- Substantive knowledge has been gained from injection management, site-specific research and observation, and government response. Experience acquired from project siting, monitoring, injection management, regulation, and public acceptance has been, in general, effective, pragmatic and allowed a balance between proceeding with projects and the management of risk.
- Large scale CO_2 injection planning should proceed. The summary of experience shows that induced seismic risk from injection is within the range of ordinary project uncertainties and can be reduced by available technologies during characterization, permitting, and operation.
- Investment in both historical data on seismicity and state of stress and data collection focused in the project area is needed for input into geomechanical models to assess risk. Based on analysis of existing data, many areas of highest risk can be identified and excluded during site selection or managed during system design and operation. Many locations based on past experience and detailed characterisation have been shown to have low risk of seismicity.
- Collection and interpretation of data during injection can further reduce risk. If a trend toward unacceptably high magnitude, frequency or likelihood is modelled based on initial responses, changes in injection strategy can be planned to reduce risk. Examples of such changes are shown in the Decatur projects, which moved the injection interval to a shallower zone to reduce the pressure communication with basement, and the Cogdell project, which reduced seismicity by changing the injection/withdrawal patterns.

Recommendations

- Pressure elevation can extend over a large area, therefore the possibility of detectible seismicity in the project area cannot be eliminated. Project developers are recommended to prepare for this contingency. Recommended plans should include:
  - modelling the range of possible responses to changes in state of stress
  - monitoring seismicity during injection and improving models
  - preparation of a risk mitigation plan that anticipates the occurrence of unexpected events
  - developing a transparent and trusted communication process with stakeholders, such that they are regularly well-informed about the processes in place (risk mitigation plan) to manage seismicity.
  - Modification of risk mitigation plans as projects progress into an operational phase and monitoring data becomes available.
  - Monitoring and detection of localised low magnitude events can be used to inform operators of potential issues and enable them to take early communication and preventitive action. Seismic monitoring of background conditions prior to site operations is therefore recommended.
  - Experience from public disclosures, and community outreach from cited projects should be shared broadly at national and international level and not confined to technical reports.
- The following recommendations for further research to advance and mature the prediction and management of seismicity:
  - Further analysis and synthesis of all the data collection and analysis now underway will be needed.

- Increased research on issues such as velocity modelling to locate hypocenters, mechanics of event triggering, methods for more effective identification of risk factors during characterisation.
- Development of low cost - high value monitoring tools and analysis to further reduce risk and increase public and investor confidence.

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Current State of Knowledge Regarding the Risk of Induced Seismicity at CO_2 Storage Projects

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Executive Summary

Large volume geologic storage as part of Carbon Capture and Storage (CCS) is one of the high value technologies to reduce atmospheric CO_2 buildup. However, public, government, investor and regulator concerns about the risk of induced seismicity have been growing over the past decade. In this report, we review the status of seismic monitoring at CCS projects and provide an update on the recent experience with partial analogs such as water injection for hydraulic fracturing stimulation and water disposal.

We reviewed 36 CO_2 storage projects listed in global indexes and determined that for 31 of them information about seismic monitoring was found. 60% of them reported conducted microseismic/seismic monitoring. Our compilation of the seismic data collected from these projects shows that rigorous and quantitative comparison of magnitude, frequency, location and correlation to injection volume and rate of is precluded because the measurement and analytical approaches are dissimilar and the number of projects reporting measurements is still small, our summery reporting is therefore descriptive with reference to the reports where more detailed analysis is available. No CO_2 storage projects have reported felt seismicity. One CO_2 enhanced oil recovery (EOR) project, Cogdell Field in West Texas, has reported felt seismicity, however public acceptance in this sparsely populated area has not been a problem and injection continues. In several projects (for examples Decatur project), analysis of small magnitude events showed promise in tracking the pressure evolution in the reservoir, which may be an important future use of this technology. Most of the projects reporting detection had low levels of low magnitude seismicity that was likely related to injection operations, however, either the data quality and sparsity or low energy precluded making detailed interpretations, and 23% reported no detectible seismicity with the various arrays and analysis installed at these sites. Two projects in Japan reported no detectible seismicity in the project area but experienced large earthquakes with epicenters in the deep crust which was interpreted by the research team as not related to the project; project infrastructure was not harmed and public acceptance was maintained. The inventory of projects that did not undertake seismic monitoring is dominated by small early projects, offshore projects, and by CO_2 EOR projects, which may be justified for all based on low earthquake risk profiles. The five projects for which we could find no information about seismic monitoring were found to also belong to this low-risk category. Analysis of available results show that technical skill developed in the oil and gas industry in microseismic monitoring is high and growing, however application of these skills to CCS site is immature and uneven. Data are too incomplete and interpretations too site specific for broad quantitative analysis of seismic response to CO_2 injection to be undertaken yet.

Concerns about induced seismicity as a result of injection of any fluid have a long history, however, more specifically, public and regulatory concerns have increased in the last two decades in partial response to clusters of felt events. Some near populated areas, are as a result of novel production methods related to hydraulic fracturing used to stimulate hydrocarbon production from fine grained rocks. We review the status of knowledge about these events, which shows that

causality is complex. Some can be tied to local injection of large volumes of saline water produced as a by-product of hydrocarbon production, others are linked to smaller more regional increase in pressure also linked to water disposal, and a few have been linked to the stimulation process itself. Poroelastic and potentially thermal loading are also playing a role in triggering some of these events.

Analysis and best practices in response to these new induced events from injection of any fluid are still rapidly evolving. The X-Y location (latitude and longitude) of events is relatively well known but hypocenter depths remain challenging to locate accurately. Many were assigned to the basement below the base of the sedimentary basin. However, better design and deployment of seismic arrays along with more accurate velocity models combined with increased experience of the interpreters and additional observations have shown that shallower horizons are not immune to induced seismicity. Increases in State-funded as well as project-funded microseismic data collection that provide information on SHmax when combined with additional information have helped to assess the susceptibility of a fault zone to slip and provide a high magnitude earthquake. Improved hypocenter location has allowed mapping of previously unknown fault segments. However, it has to be clarified that microsesimic data correspond to small mag (M<1) earthquakes.

Regulatory responses to areas with seismicity have including limiting the per well injection rate, limiting the overall injection volume in a region, limiting the injection interval and plugging back wells that penetrate deeper horizons. Mitigation has been effective in reducing the magnitude and frequency of induced events. States within the US are developing magnitude or peak ground velocity/acceleration (PGA/PGV) based stoplight approaches that allow injection to proceed but mitigate to avoid felt events and loss of public acceptance. These mitigation responses have high value for application to CSS projects.

More work is needed in prediction of induced seismic risk. Some areas where seismicity was induced could have been predicted, others however are only revealed when the events occur. A case study in Delaware basin, West Texas shows how monitoring and analysis are combined to determine the causality of induced seismicity, attributing some areas to hydraulic fracturing and others to produced brine disposal.

Advances in risk management and seismic prediction for any fluid that combine recent advances in data collection with probabilistic models in the US are presented to support the use of these evolving tools in future CCS projects. We do not yet see these tools applied widely to CCS projects, however, with increasing application of both water and CO_2 injection practices the predictive tool value should increase. Tools for translation to regions that lack experience with wastewater injection need additional development. The development and deployment of tools for this purpose is limited.

We review also the regulatory responses to seismic event related to injection of any fluid and concerns in sample areas where responses have been strong, including seven US states and two western Canadian provinces. Responses to seismic risk by regulators in Australia, Switzerland

and UK are also noted. We believe that it likely that similar responses will be applicable and successful in managing risk of induced seismicity for CCS projects as they develop.

Outreach is recognized as a key element in any injection project, and we note that concern about induced seismicity is high, but can be disproportionate to the observed incidences of events or damage. Four outreach models from geothermal sites in Oregon and the Geysers, California, regulators in Alberta Canada, and the CCS demonstration project at Tomakomai, Japan are presented as case studies. These initiatives demonstrate that proactive measures for managing public concerns, and improvement of the understanding of induced seismicity, can be effective.

1. Introduction

Any injection of fluid into a saturated volume will change the pressure in the pore fluids, which in turn will impact the state of effective stress in the rock matrix in contact with those fluids. If it reaches the critical Coulomb stress, the rock fails, triggering a response. Terminology remains somewhat problematic. If the event is large enough to be felt, it is referred to as an earthquake. Small events deliberate caused by elevation pressure (hydrofracturing) is called microseisms. In the CCS literature the small magnitude events (detectable only with instrumentation usually of M<1) can also be caused incidentally by injection. It is important to avoid public confusion between low magnitude events and felt seismic events; therefore, the low magnitude events are most commonly also referred to as microseismic events. Induced seismicity are earthquakes caused or related to human activity. Microseisms are not considered induced seismicity earthquakes. However, they can trigger microseismicity and felt seismicity associated with a nearby hydraulic stimulation fault zone. Microseismicity can be natural or induced. Table 1 summarizes different earthquake magnitude ranges and other relevant scales for seismic events. [1].

Table 1 Overview of different earthquake magnitude ranges and relevant scales for rupture length, displacement, dominant frequency and seismic moment [1].

Magnitude range	Class	Length scale	Frequency scale	Seismic moment
8-10	Great	100-1,000 km	4-40 m	1 KAk-1 MAk
6-8	Large	10-100 km	04.4 m	1 Ak- 1KAk
4-6	Moderate	1-10 km	4-40 cm	1 mAk-1 Ak
2-4	Small	0.1-1 km	4-40 mm	1 µAk- 1 mAk
0-2	Microo	10-100 m	0.4-4 mm	1 nAk- 1 µAk
-2 to 0	Nano	1-10 m	40-400 µm	1 pAk- 1 nAK
-4 to -2	Pico	0.1-2 m	4-40 µm	1 fAk- 1 pAk
-6 to -4	Femto	1-10 cm	0.4-4 µm	1 aAk- 1 fAk
-8 to -6	Atoo	1-10 mm	0.04-0.4 µm	1 tAk- 1aAk

* 1 Aki (Ak) is defined as 10^{18} Nm.
** The term “microearthquake” traditionally refers to earthquakes M<3.The earthquake class names used here are a compromise between the SI naming conventions and traditional practice.

Carbon capture and storage (CCS) requires that large volumes of CO_2 be injected into the deep subsurface for long-term storage. As the need for CCS as method to mitigate atmospheric emissions of greenhouse gases increases, the need for high quality information to be available, up-to-date, and technically grounded increases. Without good information, concerns about the risk of induced seismicity from the public, regulators, policy-makers and investors can be a barrier to widespread deployment of CCS [2], [3]. The necessity for good site characterization especially the stress status, location and magnitude of faults is proved to be critical in successful deployment of fluid injection projects. The extent of any monitoring network near proposed sites needs to be established as well as a baseline record of seismicity. Understanding triggering mechanisms should form part of the risk assessment programme of any future site especially the ability to forecast induced seismicity. In extreme cases, failure in proper site characterization has led to the immediate shut down and subsequent closure of the project at considerable cost. For example, the offshore Castor Underground Gas Storage (UGS) project in the Valencia gulf, east Spain had to be halted after gas injection triggered three magnitude 4 earthquakes, each larger than any ever induced by UGS. It is proposed that an aseismic slip brought an unmapped critically stressed fault in the hydraulically disconnected crystalline basement to failure [4], [5].

In this review, we synthesize and update available information regarding induced seismicity from CO_2 projects, from small pilots to commercial-scale efforts. However, because the number of CO_2 storage projects with relevant data are limited, we extend the best-practices data collection on recent work on seismicity, seismicity management and mitigation measures related to other types of injection, including large volume waste water injection, geothermal energy production, and hydraulic fracturing for unconventional oil and gas production as well as thermal recovery methods in heavy oil reservoirs such as cyclic steam stimulation. We have access to data from areas with many observed seismic responses to injection related to unconventional hydrocarbon production. Expanded unconventional oil and gas development has led to increased seismicity in several areas across the globe, including areas where it was previously very uncommon. The primary cause of these earthquakes is large-scale wastewater injection and/or hydraulic fracturing of the unconventional formations which sets a series of challenges to be faced by the unconventional oil and gas industry [6].

We then transfer the findings to large scale CO_2 projects (>50 million tonnes, multi-well operations), using the available CO_2 injection experience as a guide [7], [8], [9]. In principle, the physical rules that govern induced seismicity are the same for both waste water disposal and CO_2 injection but potential long-term impacts and observed magnitude of the events could be different for large scale CO_2 injection [10]. In addition to having a cold, compressible fluid injected, target geological formations may have different characteristics (depth, seal quality, etc.) that may impact seismicity potential at the injection site. Most of the basic definitions in this document can be found here [11].

2. Current State of Induced Seismicity in CCS Projects

We used the Global CCS institute CCS project inventory [12] and personal knowledge to identify essentially all projects globally that injected CO_2 into the deep subsurface and undertook some kind of monitoring, reaching a total of 36 cases. Projects still in the design phase were not inventoried as we were advised that it was too early to release information on seismic or microseismic monitoring plans. We collected data by subdividing the population by associated type of operation (enhanced oil recovery (EOR) or saline aquifer storage), however other desirable data such as pressure elevation and any metrics of state of stress were not available for many of the projects in a form that allowed effective compilation. In additional about 100 projects, mostly in the US, injected CO_2 for commercial EOR, but, as far as we could determine, did not publicly provide monitoring data other than mechanical integrity and injection data required by state regulators. Seismic and microseismic monitoring has not been required for EOR projects by US state regulators. We were advised during discussions with selected EOR operators that field specific data on seismicity are not normally collected as part of most EOR operations. In our experience, in the state of Texas with many EOR projects and to the best of our knowledge, no clusters of detected seismic signal from regional seismic arrays or locally felt seismicity at EOR operations have been reported, with the exception of Cogdell Field, TX, which is discussed below.

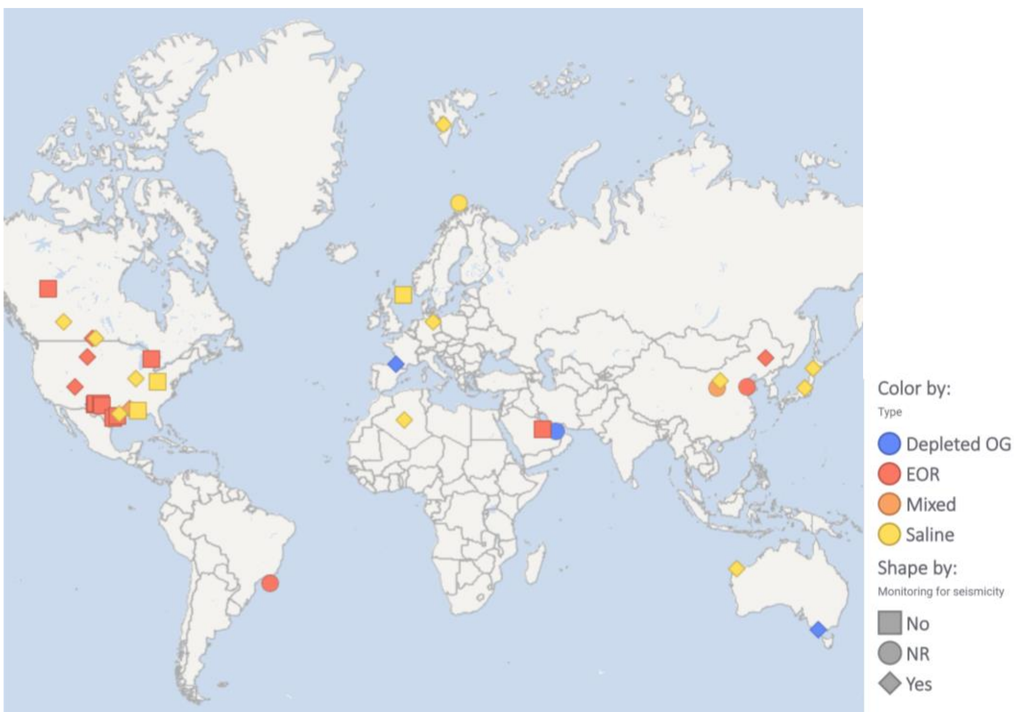


Figure 1 Geographical map of the data inventory.

Of the 36 projects inventoried (Table 2; Figure 1), 19 projects undertook any type of monitoring for microseismicity/seismicity and 12 did not undertake monitoring (Figure 2). We have lumped multiple phases of large projects, some with variable well patterns, into a single project (SECARB, Otway, Decatur/ADM). Six projects did not report seismic monitoring in inperson interviews or from the literature survey, of these one project (Gorgon) is collecting microseismic data but has not yet publicly released any findings. Other projects in China and the Middle East were not able to provide information in response to inquiry and are categorized here as non-reporting (NR). We considered evaluation of projects in stages of planning but in general the monitoring plan has not been formalized with regulators and in consultation with project developers determined that release of information on microseismic plans was considered to be premature.

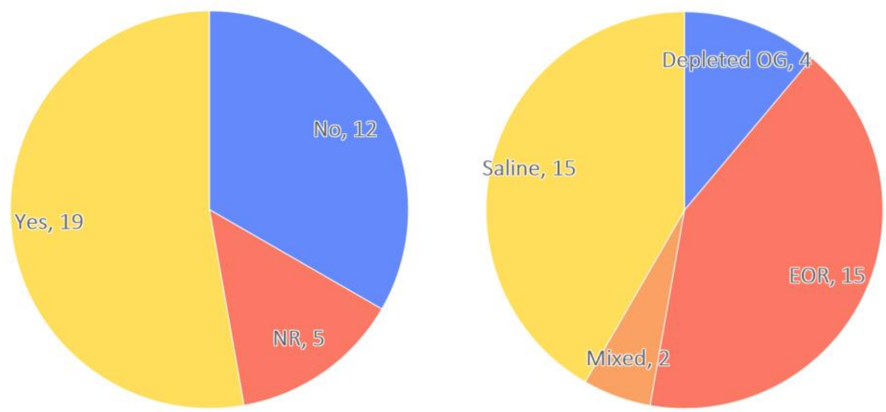


Figure 2 left) Number of projects that have reported seismicity/microseismicity monitoring, right) Type of field projects in data inventory.

Of the population of projects with reported microseismic monitoring, 15 are EOR operations, 4 projects inject CO_2 into depleted gas fields, 15 projects use saline aquifer storage, and 2 projects are mixed EOR and saline aquifer storage. Seven projects are completed and the rest are ongoing, however the level of monitoring is variable, the maximum reported injection amount is >70 million tonnes at the SACROC EOR project, which has been injecting an average of >2 million tonnes of not recycled CO_2 per year, although details are not available. SACROC field was not monitored for microseismicity in reported studies, however, no detections are flagged in detailed regional studies, as compared to the nearby Cogdell Field which was seismically active.

Of the 19 projects that undertook seismic/microseismic monitoring, 10 detected some microseismic signal attributed to injection and 9 detected no signal that could be reliably attributed to injection (Figure 3). Of these non-detect sites, two (Nagaoka and Tomakomai, in Japan) detected nearby major felt earthquakes that are shown by analysis conducted by the research teams to be unrelated to the injection. Only one site Cogdell, experienced seismicity that was reported as felt.

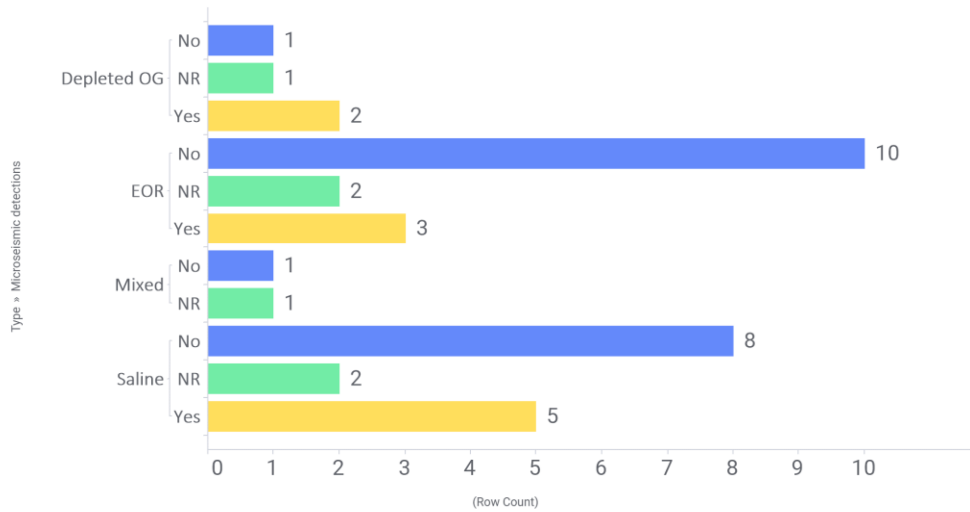


Figure 3 Number of seismicity and/or microseismicity detection categorized based on the type of the projects. NR=non-reporting

A more complete analysis of microseismic responses to CO_2 injection, including factors such as the design of the microseismic instrument array, the detection thresholds by that array, the ambient amplitude and orientation of differential stress, velocity modes of the entire rock sequence, faults fractures and other heterogeneities in the reservoir and over and underlying rock units, the history of pressure changes including magnitude and distribution of over- and under-pressure would be highly desirable. However, the available data collected and reviewed in this report across the portfolio of projects are too incomplete to conduct such an analysis to compare sites. However, some individual sites thought to be representative collected more detailed information. They are reviewed in the following sections. In our discussion, we start with non-detect examples, because for a well-selected and well-designed project, this may be a typical but not widely-recognized outcome.

Table 2 Summary of CO_2 injection sites with detection or non-detect seismicity.

Project	**Type**	**Country**	Non-detect Seismic Monitoring	Non-detect microseismic monitoring but large earthquakes nearby	Microseismic detections by the instrumentation deployed at each site (detection threshold variable)	Monitoring for seismicity	Felt seismicity related to CO2 injection
Kinder Morgan SACROC unit	EOR	USA	No	No	No	No	No
OXY Cogdell EOR project	EOR	USA	No	No	No	No	Yes
OXY- Hobbs	EOR	USA	No	No	No	No	No
Oxy Denver unit	EOR	USA	No	No	No	No	No
Sleipner	Saline	Norway	No	No	No	No	No
AEP Mountaineer	Saline	USA	No	No	No	No	No
Zama - EERC	EOR	Canada	No	No	No	No	No
SECARB Anthropogenic Saline	Saline	USA	No	No	No	No	No
MRCSP- Core Energy	EOR	USA	No	No	No	No	No
Uthmaniya	EOR	Saudi	No	No	No	No	No
Air Products Industrial capture	EOR	USA	No	No	No	No	No
Petra Nova	EOR	USA	No	No	No	No	No
Weyburn	EOR	Canada	No	No	Yes	Yes	No
Aneth	EOR	USA	No	No	Yes	Yes	No
In Salah	Saline	Algeria	No	No	Yes	Yes	No
Rousse (Lacq), France	Depleted OG	France	No	No	Yes	Yes	No
Otway phase 1, 2.3	Depleted OG	Australia	No	No	Yes	Yes	No
Decatur -Archer Daniels Midland -several stages	Saline	USA	No	No	Yes	Yes	No
Shell Quest	Saline	Canada	No	No	Yes	Yes	No
Longyearbyern	Saline	Norway	No	No	Yes	Yes	No
CNPC Jilin	EOR	China	No	No	Yes	Yes	No
Shenhua Odos CCS demonstration	Saline	China	No	No	Yes	Yes	No

Project	**Type**	**Country**	Non-detect Seismic Monitoring	Non-detect microseismic monitoring but large earthquakes nearby	Microseismic detections by the instrumentation deployed at each site (detection threshold variable)	Monitoring for seismicity	Felt seismicity related to CO2 injection
Ketzin	Saline	Germany	Yes	No	No	Yes	No
Nagaoka	Saline	Japan	Yes	Yes	No	Yes	No
Tomakomai	Saline	Japan	Yes	Yes	No	Yes	No
West Pearl Queen	Depleted OG	USA	Yes	No	No	Yes	No
Frio saline	Saline	USA	Yes	No	No	Yes	No
SECARB Early	Mixed	USA	Yes	No	No	Yes	No
Bell Creek (EERC)	EOR	USA	Yes	No	No	Yes	No
Aquistor	Saline	Canada	Yes	No	No	Yes	No
Snøhvit	Saline	Norway	NR*	NR	NR	NR	NR
Lula	EOR	Brazil	NR	NR	NR	NR	NR
Gorgon	Saline	Australia	NR	NR	NR	Yes	NR
Abu Dhabi Emerates Steel to ADNOC (Al Reyadah)	Depleted OG	United Arab Emirates	NR	NR	NR	NR	NR
Sinopec Qilu	EOR	China	NR	NR	NR	NR	NR
Yangchang CCS facility	Mixed	China	NR	NR	NR	NR	NR

*NR= non-reporting

2.1.1. Non-detect Seismic Monitoring

It is likely that all injection creates some acoustic events (where most of the events are in the microseismic range even though some are not detected with sensitive seismic equipment) in the well and rock system as pressure and temperature vary during injection. When receivers are placed in the reservoir zone, noise is detectable [13]. However, whether the energy content of this noise is adequate to be detected depends on the source and frequency of acoustic signal, the placement, sensitivity, and frequency content of receivers, and the noise present in the field site. The reasons for non-detection seem to be variable from site-to-site, and selected examples are discussed below.

SECARB, USA

The SECARB "early test" at Cranfield, Mississippi is a case study of non-detection of microseismicity related to a high pressure, high volume injection that started in 2008 and is ongoing, with about 1 MMT/year injected during 3 years of microseismic monitoring. This injection was hosted by a commercial CO_2 EOR project operated by Denbury Onshore LLC, but unlike most EOR projects, the reservoir that had undergone pressure recovery for 40 years prior to EOR development so it was normally pressured at the start of injection. The first year of the project was similar in most ways to a saline aquifer test, where pressure is elevated above hydrostatic, as much as 7 MPa above initial pressure (measured at a monitoring well with a downhole gage). CO_2 was the only fluid injected into the reservoir; there was no water injection, and additional CO_2 was injected in the water leg downdip of the reservoir. The EOR flood and water leg response to CO_2 injection were extensively monitoring as part of as part of DOE's Regional Carbon Sequestration Partnerships (RCSP) program. After hydrocarbon production began, pressure decreased but remained above initial values, especially in zones still being prepped ahead of production [14]; [15].

The Cranfield reservoir is a chlorite-cemented sandstone of the Tuscaloosa Formation of Cretaceous age at depths of 3 km and lies in a near circular 4-way closed anticline (incipient diapir from Jurassic salt at depth). Two normal faults form a graben that compartmentalizes the field. Geomechanics was a focus of the project, however some of the early installed tools such as downhole microseismic arrays and tiltmeters failed because instrument pressure and temperature limitations for sustained deployment were exceeded. Surface installations did not detect seismic noise that could be separated from surface noise. A second opportunity to collected microseismicity occurred via a collaboration with the Japanese Research Institute of Innovative Technology for the Earth (RITE), which installed a 3-km radius ring of 6 seismometers installed at a depth of 90 m and collected data for >3 years [16] [17].

Conclusions of the RITE microseismic monitoring performed at the Cranfield site are:

1) During the second (successful) deployment, no microseismic events were detected with locations at the Cranfield site during the more than three years of high quality monitoring. Detected signals were all identified as background noises, artificial noises, noises due to weather and distant natural earthquakes with M>2.5 at distances of more than 300km.

2) The monitoring system worked satisfactorily overall. Although a recording system at one station briefly failed, it did not hinder the quality of the monitoring results because of designed redundancy in the array. RITE deployed stand-alone monitoring stations; therefore, monitoring data recorded at other stations were not affected.

Spectral model analysis showed that microseismic events with Mw of -0.5 are detectable at a distance of 3km. A recorded perforation shot was estimated with magnitude between -0.5 and 0. Even high pressure changes next to the faults that intersect the reservoir did not trigger events above the detection threshold of Mw -0.5 at Cranfield during CO_2 injection [15]. In this project, information on state-of-stress was not collected.

West Pearl-Queen, USA

The West Pearl Queen (WPQ) field carbon dioxide (CO_2) sequestration experimental site is located near Hobbs, New Mexico. For fifty days (December 20, 2002, to February 11, 2003) 2090 tons of CO_2 were injected into the Shattuck Sandstone Member of the Queen Formation at the West Pearl Queen site. [18]. During this period, bottom-hole pressure reached as high as 19.9

MPa which limited CO_2 injection rate to 40t/day. A receiver array in a well adjacent to the injector did not record significant microseismic events [19]. The operator's intent to limit injection pressure to below fracture pressure seemed to have been correct and effective in limiting felt seismicity and/or microseismicity (if microseismic monitoring tools are deployed) to below the (unspecified) detection threshold.

Bell Creek EOR

Bell Creek is an oil field in the Muddy Formation, Montana of Cretaceous age that was brought under CO_2 flood for EOR by Denbury in 2013. The reservoir at depths of 1,350-1,372 m was water flooded to increase pressure prior to CO_2 injection. During CO_2 injection, research-oriented monitoring was conducted by the Earth & Environmental Research Center, University of North Dakota (EERC) as part of DOE RCSP program. They installed a permanent downhole array of 50 3C geophones at depth of 18-753 m. The EOR operation was found to be noisy, with most reported events occurring during the day when the oilfield activities were most active. Representative nocturnal events were analyzed [20]. However, no data that was interpretable as reservoir response was found. High noise from EOR operations and the environment may have masked small signals.

Ketzin Germany

The densely instrumented pilot experiment conducted at Ketzin, Germany, injected 67,000 tons of CO_2 in several stages starting in 2008 into dipping Triassic sandstones at depths of 630-650 m on the flank of a deep-seated salt-cored structure. Seismic monitoring was added as the project was already underway. It included TNO's, a Dutch research institute, 120 m-long fixed seismic array placed at the edge of the project test facility including 13 3C geophones at the surface and a hydrophone at 50 m depth, and 5 3C geophones at 10 m depth. A few events with local magnitude M_L =[-2.5 – 0.5] were attributed to the reservoir interval, however the small events were not fully analyzed [21]. A combination of slow injection rate and favorable state of stress in the field has kept the effective stress level below the failure levels and have limited the amount of microseismicity. Modeling studies have shown that there is no failure in the caprock and faults remain stable during CO2 injection operations [22].

Reef projects – Zama, Redwater (canceled), MRCSP -Core Energy Michigan reefs.

A number of projects injecting CO_2 into depleted permeable carbonate reefs reservoirs enclosed in low permeability anhydrite or rock salt have been studied. These are interesting when compared to other sites because the injection unit is hydrologically isolated because of closure on all sides. At the start of injection, pressure can be strongly depleted but pressure increase is relatively rapid. The resulting elevated pressure can be high and stay sustained post injection, depending on the planned operation. However, though recognizing the value of microseismic monitoring for monitoring within the reef and possible risk of induced seismicity, deployment of monitoring has been modest. At the Zama depleted oil field in northern Alberta, CO_2 was injected into 90 m of the high-permeability reef deposits of the Keg River Formation. The associated geomechanical study was limited to core testing and analytical models [23]. The proposed Heartland area injection into the Redwater reef has not started yet, and estimates about the expected geomechanical response to injection are limited. A study of the microseismic response of injection into several pinnacle reefs operated by Core Energy and studied by the MRCSP (Battelle Memorial Institute) has recently been completed but was not released in time to include in this survey.

Otway, Victoria, Australia

A series of research-oriented projects were undertaken starting in 2008 and continuing through multiple phases at a site in Victoria, Australia including a number of studies that considered geomechanics [24]. The area is faulted which has a strong impact on injection however injection was intermittent and volumes are small, so no risk of fault activation and resultant induced seismicity occurred or is expected to occur [25]. However, the area has natural background microseismicity which has been measured with surface equipment and prior to the injection tests with levels around M 0.1. Monitoring during injection as the CO_2 reached the fault led to sparse observations showing no temporal or spatial correlation to injection. During a second injection, downhole triaxial arrays measured only one event on all six geophones, with other events considered likely to be noise. No advanced seismological waveform analysis has been undertaken to investigate other signals and have been attributed to noise. Instrument design and issues such as power supply intermittency are noted as limits on the detection certainty. A third phase of testing is planned in the near future at this site. [26]

2.1.2. Non-detect microseismic monitoring but large earthquakes nearby

In Japan, two CO_2 injection demonstration projects have experienced natural earthquakes and provide valuable case studies because of the expertise and investment of the project teams. Both projects had seismicity risk as a design focus because of their location in Japan, which is a seismically active region.

Nagaoka and Tomakomai pilot projects, Japan

The small-scale pilot test stated in 2003 in a saline formation at Nagaoka experienced a 6.6 Mw earthquake in 2004 during injection and one during the post injection period. Injection was stopped because of the events, but no damage or causality was demonstrated and the program continued to completion. No seismicity was detected in the vicinity of the injection reservoir. Studies suggest that this event was unrelated [27], [28].

The Tomakomai pilot project is located approximately 3 km offshore beneath Tomakomai Bay, in Hokkaido, Japan and is run by Japan CCS (https://www.japanccs.com/en/). CO_2 was injected mostly into the sandstones of the Moebetsu Formation at 1.0-1.2 km depth; a test injection program was also conducted in the volcanic rocks of Takinoue Fm. (depth 2.4-3 km which, in the target area, was found to be low permeability). Injection was conducted between 2016- 2019. No injection-related microseismicity was observed when compared to pre-injection baseline, using a threshold of Mw > -0.5 [29], [30]. The project installed an onshore seismometer in Tomakomai City, three ocean bottom seismometers (OBS), and an ocean bottom cable (OBC) with capacity to record natural earthquakes and any microseismicity, and downhole 3-component seismic sensors in two observation wells at near-reservoir depths. Prior to injection, 9 events located at depths far below the injection zone (5.9-8.6km), with magnitude -0.9 to 0.24 were observed near the project area. During the injection period, 3 events at similar depths and Mw 0.31 -0.52 were recorded [30]. Another important contribution of this project is related to the magnitude 6.7 Hokkaido Easter Iburi Earthquake, which occurred September 6, 2018. Its epicenter was located 30 km north east of the project area, at a depth of 37 km related to a previously mapped regional complexly faulted and subduction system. The project team set an example of rapid technical analysis and public communication to document that the Iburi event was not related to the CCS project, and that the project was properly designed and therefore undamaged. [28]

2.1.3. Microseismic detections

In a number of projects, detection and analysis of microseismic (M<1) events helped to understand flow processes in the subsurface. The analysis of geomechanical response of the reservoir has value in determining what the risk of felt seismicity is as a result of the pressure perturbations caused by the project, and clarifying the mechanism by which such risk can be reduced.

In Salah, Algeria

In Salah CCS project in Algeria, which was run 2004-2011 is an important case study. It is so far the only CO_2 geologic storage project where geomechanics was well documented because it was unexpectedly problematic for the operation. However, seismicity itself was not an issue as magnitudes remained Mw<1. At the In Salah gas processing plant location near the Krechba Field, Algeria, 3.8 MMT of CO_2 were injected into the downdip water leg at a depth of about 1.9 km into the same 20 m-thick Carboniferous sandstone that produces gas on the crest of the structure. Three horizontal injection wells perpendicular to the regional fracture patterns were used for injection because the matrix permeability of the injection unit is low (1 mD). However, apparently because of an error by the local operator, CO_2 was injected at rates that resulted in downhole pressure exceeding the fracture pressure at the cool conditions created by rapid injection [31] [32]. Detection of distinctive U-shaped pattern surface deformation greater than what would be produced by the pressure at reservoir depths was an indication that fluids and pressure were migrating up fractures to shallower-than-intended zones. The details of the geomechanical response are under constrained [33]. Microseismic monitoring used a single 48 level 3-C geophone string at 30- to 500 m depths in a well which had various equipment malfunctions during injection that limit hypocenter location but show temporal correlations with periods of high injection rate and bottom hole pressure [34] [35] [36].

Lacq Pilot, France

53,000 tonnes of CO_2 captured from the Lacq gas processing facility in southern France was pipelined 27 km to the Rousse depleted gas field where it was injected for storage into the highly faulted and fractured Jurassic Mano carbonates [37]. The reservoir is at depths greater than 4 km in a graben, which was depressured to 3 MPa at the end of production (initial pressure was 480 bars). The area has regional seismicity, and seismic events occurred during production of the Lacq gas field. From 1967 until 1989, 1000 earthquakes recorded in the area; 44 with magnitudes greater than 3, and 4 with magnitudes greater than 4 [38]. However, the Rousse field exhibited no such response. Continuous microseismic monitoring with sensors 150 m above the top of reservoir on the injection well and with a network of six 200-m deep wells in a ring around the injector and one in the center. During the baseline survey period, 200 natural earthquakes were located within 30km of the injection well. After the start of pre-injection in 2010, 3 local seismic events, with magnitude between -0.7 and -0.3, have been located in deep structures and are thus considered unrelated to injection. 3 “induced” events, with magnitudes ranging from -1.1 to -0.3, were also detected just after the end of this first pre-injection phase. These were located both around the injection well and close to a mapped fault. During the main injection phase (March 2011 – March 2013), 27 local seismic events, with magnitudes ranging from -1.0 to 1.8, have been located on the deep structures within the perimeter of interest; and 11 induced events having magnitudes ranging from -1.1 to -0.4 were also detected. Induced seismicity was found to present no detectable risk to containment and project operation. [39]

ADM, USA

Several storage projects injecting CO_2 generated from the Archer Daniels Midland (ADM) ethanol plant in Decatur IL into the basal Cambrian Mount Simon Sandstone have been conducted and added substantial knowledge about microseismicity during storage [40].

The initial project, started in 2001, aimed to inject just less than the permitted amount of CO_2 (1MMT) over three years into several zones of the regionally extensive sandstones of the Mount Simon Formation, which is a regionally important target for CO_2 storage. The project permit stated that ADM permit required continuous performance of passive seismic monitoring using a combination of borehole and surface seismic stations to detect local events over Mo 1.0 within the Area of Review (AoR). The Mount Simon Sandstone is 450 m thick in the project area, and overlies the think and low permeability pre-Mt Simon sandstone and Precambrian basement. The reservoir, underlying rocks, as well as overlying confining zones were cored and an extensive monitoring system was developed [41], [42].

The injection well was perforated at depths of 2,128-2,149 m and the well instrumented with geophones at 1,750 m and 1,870m. Eighteen months of pre-injection baseline was collected. A separate well dedicated to a 5-level geophone array at depths 1,875-2,118 m was installed after the initial seismic events were detected to improve monitoring; half the observed events can be located. In addition, a study by USGS detected 3,400 microseismic events ranged –from M_M 1.07 to 1.52 that were located in the injection period where data are clean and highly interpretable. Events are located in the low permeability zone in the lower Mt Simon, Pre-Mt Simon, and

Precambrian basement [41]. Modeling indicates that the microseismicity is associated with evolution of the pressure field, not the CO_2 plume itself, and events are more common during perturbations in flow, including shutdowns than they are during steady operation [43], [44], [45]. The ADM site passive seismic monitoring is a combination of borehole and surface seismic stations deployed to detect local events over M 1.0 within the AoR [46]. ADM project showed the relationship between injection cycles, seismicity and the location of microseismic events which is significant for future CCS project developments.

Aneth Oil Field, USA

Aneth oil Field, San Juan County, Utah. Injection here for EOR into the Pennsylvanian Edge Desert Creek carbonate of the Paradox Group, at a depth of 1 km, Stresses continue to build up by forces or displacements acting on the upper crust, and are locally released by seismically and aseismically slipping faults or new fractures. Slip in turn loads adjacent parts of the crust.

Well 707-1,768 m was started in 2006. Water flood was followed by a CO_2 flood and 24 three-component geophones were installed at well 800-1. Stresses continue to build up by forces or displacements acting on the upper crust, and are locally released by seismically and aseismically slipping faults or new fractures. Slip in turn loads adjacent parts of the crust at 700 m depth. Detection of magnitude -1 to 0 events located on the flank of the producing reservoir illuminated a NW-SE fracture zone [47] [48] [49].

Weyburn Midale CO_2 EOR project

The Weyburn Midale CO_2 EOR project emerged in 2000 as an early full-scale research site as interest for CO_2 storage developed. The project consists in two adjacent EOR fields using CO_2 initially captured at the Dakota coal gasifier plant and later at Sakspower Boundary Dam power station. The project provided a high value early opportunity to collect data about CO_2 injection and provided a rich body of information. The field was developed using horizonal injection and production wells oriented to intersect known fracture systems; the Souris River faults found at depth in the area. Seismic events ranged from -3 to -1 are located generally in or above the injection zone in the Midale Formation at depths of 1,450 m. However, because of low waveform quality, there has been an error in vertical source location of the events ranging from a few meters to more than 100 m in some cases [50] , so that events might also be located in the underburden. Events are clustered both temporally during operations and spatially on production wells [23] [50].

Longyearbyen on Svalbard, Norway

A demonstration project near Longyearbyen on Svalbard, Norway was the subject of a study that started injection in 2010. No CO_2 was captured from the local coal-fired power plant, but a fractured low permeability sandstone (1-2 mD) reservoir in the Upper Triassic and Middle Jurassic De Gerdaalen and Knorringfjellet formations at depths of 1,000 m was tested by water injection to check if it was suitable for future storage. A 5-level 3C string to a depth of 300 m, an 8-level geophone string to a depth of 590 m and 3 3C geophones in 120m-deep boreholes. A microseismic event of M ~1 followed by seven aftershocks was recorded near the injection well. Subsequent injection did not generate any microseismicity, however, analysis of flow parameters suggested fracture opening was occurring. Ambient noise, methane leakage, permafrost influence on the recorded signal, and equipment damage as a result of harsh environmental conditions are aspects of detection considered at this pilot that may have application to other projects. [51]

2.1.4. Felt seismicity related to CO_2 injection

Only one CO_2 project is known to have had felt microseismicity that has been attributed to CO_2 injection.

Cogdell Field, Scurry-Kent Counties Texas, USA

Cogdell Field produces oil from the Pennsylvanian age Canyon Reef limestone in the Midland Basin in West Texas, at a depth of 2.1 km. Secondary oil recovery by injection of recycled brine was initiated in 1956. Seismic events were noticed starting in about 1974, with a magnitude 4.3-5.3 event recorded in 1978, before CO_2 injection began, with an epicenter depth 1.9 km. CO_2 injection began in 2004. The US Array microseismic network [52] was deployed in this area and was able to measure a renewed episode of microseismicity associated with CO_2 and water injection. Analysis is limited by limited downhole pressure data, limited injection/production details, and limited subsurface data [53]; [54]. Injection has continued throughout the seismicity. Informal reports indicate that the operator made some adjustment to the injection and production rates, however detailed data or analysis are not publicly available. The field is about 60 km north of the town of Snyder TX, and is a sparsely populated area. The CO_2-injection at Codgell was associated with 18 M>3 events and a Mw 4.4 event in 2011 [55]. We found numerous technical reports and studies but no indicator of widespread public concerns. Additional study of this outlier EOR project with significant seismicity is warranted to understand the causes and best management practice.

2.1.5. No monitoring for seismicity

In our inventory 12 storage projects have not attempted any type of monitoring for seismicity. The rationale for this decision is typically not expressed in publication. However, we have probed the thinking behind the "no monitor" decision via conversations with those involved. Several interrelated motivations are expressed: 1) no risk of seismicity because the injection pressure to be generated was felt or shown via a combination of experience and calculations to be well below the threshold for inducing seismicity in or near the selected injection zone; 2) no monitoring required by any party to the project (regulator, funder) or not part of the scope (research); and 3) high cost and little value of seismic monitoring, e.g., offshore settings where microseismicity would not be felt and instrumentation was expensive. The decision not to monitor was more prevalent in early CCS projects, but monitoring has increased which reflects the rise in awareness and interest in seismicity.

Some examples in the no seismic monitoring category are small early projects (Mountaineer, West Pearl Queen, most small projects in the US DOE's Regional Carbon Sequestration Regional Partnerships Phase II, and the SECARB anthropogenic test at Citronelle). Projects where the operator had previous experience and low research drivers (e.g., commercial projects) have mostly elected not to monitor; in this category, fall almost all commercial EOR projects (Permian Basin, those in Mississippi, Louisiana and Texas operated by Denbury (Hastings) and Hilcorp (West Ranch). It should be noted that pressure elevation in EOR is limited by typical low pressures at the project start. EOR usually follows mature water floods and occurs in the late stages of a project, when pressure is locally and sometimes regionally depleted by the long production history. In addition, because the operator's profit is enhanced by producing as fast as is feasible while maintaining miscibility, pressure is aggressively managed. The closely-spaced injection and production wells to form "patterns" that are designed to equalize pressure across the reservoir, and this results in reducing the area outside the reservoir where pressure is perturbed. These factors tend to limit pressure away from injection wells to near original pressure. The operator of the Cogdell field where EOR did produce seismicity is the exception. However, a detailed analysis of field operation to determine the cause has not occurred.

Microseismic monitoring has not been undertaken at most offshore injection projects. For large volumes and sustained high rate injection at Sleipner in the Norwegian North Sea [56], a study of microseismic risk indicated that, although the state of stress was sufficient to result in potential triggering of fault slip at pressure >0.02 MPa, the mechanical characteristics of the unconsolidated Utsira Formation prevented rupture. However, in the vicinity of the Sleipnir field (1 km distance) a M3.5 event was observed, which could be associated with the field (the location errors in this part of the North Sea are very large).

For five projects we were unable to obtain clear confirmation on whether microseismic data was collected. These projects fall into the small, offshore or EOR categories and may not have monitored seismicity.

3. Recent work on Induced Seismicity from water injection sites - USA

Induced earthquakes have been known for several decades. Analysis of felt seismicity as consequence of water disposal in deep saline formations was conducted for the Rocky Mountain Arsenal M5.2 earthquake in 1962 [57]. An inventory of many other events from water injection and geothermal activities was compiled in a previous study and applied to CCS [58], [55]. We do not review here this previous work, but update it.

We believe that the analogy between seismic events induced by water and those that might be induced by CO_2 injection is relevant, and that learnings from water injection can directly be translated to advice for large scale CO_2 injections. Several reasons for this confidence are presented. Although CO_2 is a more compressible fluid than water, the effect on pore pressure is the same as water. Some difference in terms of the interaction with the CO_2 and mineral frame, for example, rock dissolution or other types of softening can be considered, as well as difference in near-well cooling because of different thermal properties of CO_2. At many sites, much of the area of pressure increase in a CO_2 injection is in the water phase outside of the CO_2 plume and is identical to water injection cases. We therefore review in detail learnings from recent analogs.

The recent increase in public concern and study of induced earthquakes to be added to previous studies in this review are those attributed to oil and gas production from unconventional formations ("shales"). Some of the earliest earthquakes occurred in 2008 in the Fort Worth Basin of north-central Texas where the target formation, the Barnett Shale, is located. The Barnett play was the first beneficiary of the combination of high-volume hydraulic fracturing technology and horizontal drilling that took off in 2005 [59]. Dallas Fort Worth International Airport earthquake sequence of Oct.–Nov. 2008 marks the beginning of an ongoing series of seismic events when 10 felt earthquakes (range from 2.6 to 3.3) were recorded [60], [61], [62]. The sequence was interpreted by some, but not all, as the result of produced water disposal in a couple of salt water disposal wells (SWD) located on the DFW airport. The events alarmed local residents and the State of Texas initiated a review of its regulations that is still ongoing.

Following this initial sequence, seismic events related to high volumes of water disposal were observed elsewhere in the Fort Worth Basin (Mw 4.0 2015 Venus sequence). Seismic events have occurred in other shale plays in Texas, and in other oil and gas producing states [63]; [64]; [61], in particular, a M4.0 earthquake in December 2011 in Youngstown, Ohio [65], the <M3 Greenbrier cluster (2009-2010) and the M4.7 Guy-Greenbrier swarm in 2010-2011 in Arkansas [66], and the M5.7 earthquake in November 2011 near Prague in central Oklahoma [67]. In addition to these relatively high magnitude earthquakes, thousands of earthquakes were potentially felt (~>M3) and tens of thousands were observed (>M1.5-3). Note that some areas have a history of natural tectonic earthquakes (Rio Grande rift in New Mexico and West Texas; mid-continent rift, New Madrid seismic zone). In addition, all states have the potential for human-induced seismic events not related to salt water disposal (SWD) and due to oil production, groundwater withdrawal or dam building. Although, in the statistical sense, recent seismic events are correlated with SWD wells and pressure build-up, some events might be natural.

The south-central section of the US (New Mexico, Texas, Oklahoma, Kansas, Arkansas) seems particularly affected by numerous and sometimes large seismic events. Several researchers have postulated that this is the result of the combination of the nature of the plays with a relatively high-water production and of the position of the disposal intervals directly overlying the Proterozoic crystalline basement. The strata receiving the waste produced water consist of thick karsted marine carbonates (cavernous and locally dissolved limestones and dolostones) of Cambro-Ordovician age deposited on a really extensive continental platform. These rocks are the Ellenburger Group in Texas and New Mexico and Arbuckle Group in Oklahoma, Kansas, and Arkansas. Many of the seismic events occur deep in the basement. For example, in Oklahoma, the disposal intervals are at a depth of ~2km but the seismic hypocenters are estimated to be at ~5km in the basement. This observation has driven most of the early regulatory responses to the increased seismicity even if some plays do not dispose of the produced water in close proximity to the basement. The stacked plays (intervals at multiple depths) of the Permian Basin in west

Texas and southeast New Mexico are characterized by a high water cut, but the most used disposal intervals are located at shallower depths than the production intervals. This, however, does not prevent earthquakes from striking the region, for example, the M4.6 Mentone earthquake in Mars 2020 in the Delaware sub-basin of the Permian Basin of West Texas. Other regions of the country, such as North Dakota at the Canadian border with the Bakken formations and the Marcellus Shale in the northeast US, display smaller produced water volumes and a relative lack of felt seismicity.

3.1. Site Selection Considerations

In the earth's brittle upper crust, a combination of large-scale tectonic forces and local geophysical-geological heterogeneities gives rise to non-isotropic principal stresses of relative magnitudes and consistent orientations [81]. Stresses continue to build up by forces or displacements acting on the upper crust, and are locally released by seismically and aseismically slipping faults or new fractures. Slip in turn loads adjacent parts of the crust. As a result, most of the crust is in a frictional state of balance, in which the best oriented faults for slip with respect to the principal stress directions are close to failure [82] ; [83]. When friction of faults is unstable, and slip occurs rapidly, a short timescale phenomenon of brittle tectonics is the reason for seismicity [84].

If part of the crust is currently in a stress equilibrium, i.e. no previously known seismicity, or intraplate tectonics, this can be altered due to anthropogenic activities (injection, hydraulic stimulation, etc) that, due to pressure changes, will affect the current state of stress and initiate an earthquake cluster. However, this is not always the case since it depends on the geophysical properties of the crust that could either indicate a non-dynamically slipping fault, due to maximum stress direction, or pore pressure diffusion that will eliminate effective stress. There are cases that stress is transferred to deeper zones that are prone to be critically stressed and susceptible to slip (OK, example). Also, an earthquake to earthquake interaction is also possible that accumulate stress to previously seismically non-active regions [85].

In an area of interest for CCS one can identify the state of stress in the crust using different approaches (geodetic, InSAR, borehole breakouts, bottom hole and even wellhead pressures, seismicity monitoring, etc.). At the In Salah project, the location of the CO_2 plume and the stress changes in the caprock have been monitored [86] using 4D seismic reflection surveys, gravity, VSP, deep observation wells, InSAR [87]; [88] , and a passive geophone array [89]; [90], [91], [92]. In Decatur, various complementary seismic monitoring surveys [93]; [40], [94] started after the injection managed to provide state of stress and distribution of microseismicity ($-1.13<Mw<1.26$) during CCS. However, one should note that (a) documented fault map shows an inactive fault (no documented seismicity) 100km away from the area [95], and (b) geological studies provide various stress directions [96]; [97]. However, more than some of the stress defined by the microseismicity does not align with the regional stress [94] defined during the site selection process that is lacking of microseismicity monitoring.

However, we should be able to understand the geological/geophysical properties of the medium into which we inject CO_2 and eventually monitor any type of seismic activity during the site selection process and/or any possible injection testing. Understanding the state of stress is important; however, such information is not adequate in areas with no prior (recent or historical data) either felt or instrumental records of seismicity. This is the case especially in areas that are highly fractured and/or are of small scale, and it is important to assess the current state of stress (using relatively recent seismicity) to identify rupture zones in the earth's crust of increased seismic hazard. The main reason why low magnitude (not felt at the surface) neotectonic seismicity is important is the inability of other methods (geodetic, InSAR, borehole breakouts, etc.) to provide high accuracy information in a short time that can be directly associated to current state of stress.

Because of the limitations of pre-injection characterization, collecting data to affirm or modify characterization assumptions is needed. In case the site is close to an active tectonic zone [98] it is possible that seismicity information be available. Such data can be used to identify active rupture zones and the maximum horizontal stress direction (SHmax). In case the area of interest is lacking earthquake data and, in absence of a seismic array, the deployment of a local array is favored in order to identify any low magnitude seismicity ($M \leq 1.0$). It is important to clarify that any seismic monitoring will have to precede any activity or decision about the viability of a site for CO_2 storage. Seismic monitoring described in the following section is crucial in order to identify possible unknown faults that are difficult to identify with active seismic (i.e. strike slip faults) or other geophysical methods.

3.2. Seismic Array Installations

Most of the local seismic arrays used in induced seismicity studies, based on the location of the sensors, are: (a) surface arrays, (b) borehole arrays, and (c) hybrid type. In addition, the seismometers used are either short period or broadband velocity sensors or accelerometers.

Assuming a realistic earth model for the area, a travel time simulation can be used to identify expected magnitude of completeness (Mc) for an area. However, noise level at each sensor site affects the detection of P and S arrivals; their uncertainty and influence impact the detectability of each network and accurate earthquake location. It is highly recommended to use observed earthquake data, if available, during the site selection experiment to calculate observed Mc [99], and bias on earthquake location [100].

3.2.1. Surface Arrays

Surface arrays have the lowest cost for deployment and maintenance. However, the project needs to have a large number of stations deployed and a combination of different seismometer types in order to achieve an accurate hypocenter location and estimation of source parameters (Moment Tensor, etc). In that case, a small array (four stations following the edges of a triangle with a station in the middle) of stations of collocated accelerometers with a short period sensor (geophone) is favored close to the earthquake source (if known). Complementary to that, additional seismometers would be patterned according either: (a) co-central circular arrays with increasing radius but with a high number of stations at a distance from the area of interest similar to the depth of investigation; or (b) stations along a 2D grid, that have short interstation distance close to the area of interest (shorter than the depth of investigation) and long interstation distance away from the area of interest (up to two times the depth if investigation).

3.2.2. Borehole Arrays

Borehole arrays can provide the lowest detection threshold and the highest accuracy in earthquake location, especially if (a) there are three boreholes surrounding the area of study, and (b) there is a perforation shot to calibrate the array. Uncertainty and bias in earthquake location is then minimal. The borehole arrays will have geophone strings, extending, if possible, to the depth of investigation and a couple of km above and below it. In addition, an accelerometer and a set of three broadband seismic stations as a small surface array are useful in order to be able to provide earthquake locations and moment tensor calculation (to estimate the fault plane and the energy release) in case of higher magnitude events. In order to decrease the cost of the array, boreholes drilled during the process of site selection can be utilized to host the geophone strings. In general, good coupling of the casing to the rock and the geophone to the casing is needed and, in many cases, this requires a dedicated well with cemented-in instruments to the injection depth for optimum performance, although new designs linked to improvements in active seismic imaging are possible.

3.2.3. Hybrid Arrays

Although borehole arrays are the best approach to monitor low magnitude seismicity and earthquake migration in an area of study, there is a high cost for such a deployment. A cost-efficient approach is to use a hybrid of borehole and a surface array. A surface array can be used during the site selection process. The same array with additional surface stations, if necessary, can be complemented and improved with at least one borehole array. In order to decrease the cost of the borehole array, a borehole drilled during the process of site selection can be utilized to host the geophone string. The surface array should comprise both seismometers and accelerometers. Perforations shots at different azimuths and distances from the area of interest are important to calibrate the array and especially the geophone string. If this is not possible, the earthquake locations, including the borehole array, will be misleading.

A hybrid array (Figure 4) is presented in Okamoto et al., [101] that use 5 surface stations and 4 borehole stations to monitor the seismicity due to injection. The array provided accurate spatio-temporal clustering of seismicity and identified possible mechanisms of injection induced earthquakes.

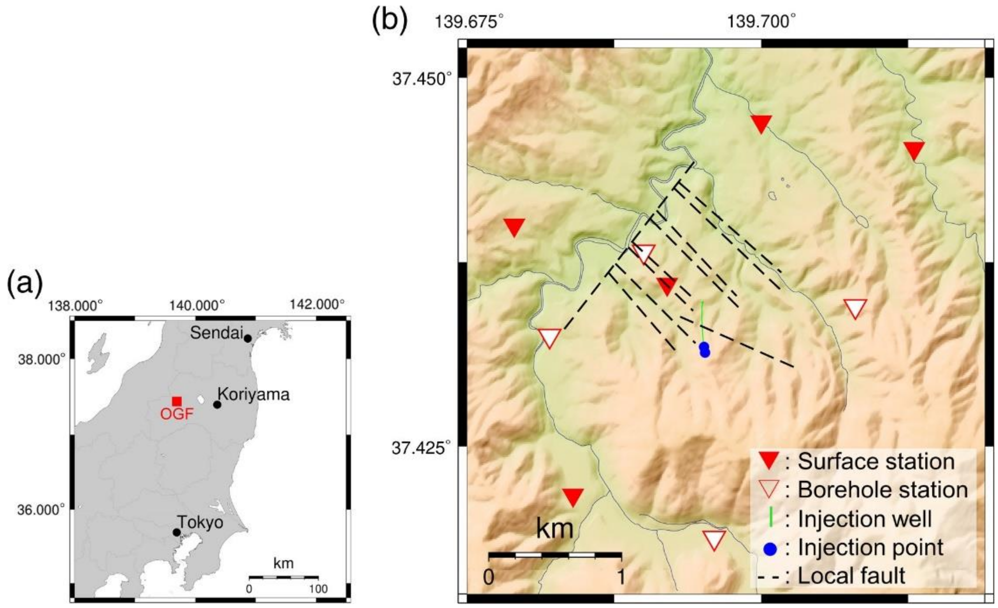


Figure 4 (a) Regional location of Okuaizu geothermal field (OGF). (b) Local geometry with estimated local faults at OGF. (Figure 1 from [101])

3.3. Seismic Event Discrimination

There are two elements to the event discrimination topic: (1) specific discrimination methods and studies, such as the study presented here for Texas or statistical studies of induced seismicity in California [102] and (2) practical experience with public perception around certain events. For the latter, the Japan CCS experience at Nagaoka site (previously discussed in this report) with nearby natural earthquakes is a good example.

Recent studies in Texas ([99]; [103]; [104]; [85]) show a clear association of seismicity with oil and gas operations. In the most recent west Texas study, Savvaidis et al., [85] present compelling results showing that induced seismicity is due to either hydraulic fracturing (HF) or saltwater (SWD) injection. Based on a space-time clustering seismicity model (Figure 5), they identified areas (Toya South, Reeves West, Jeff Davis Northeast, Jeff Davis East) with clustering seismicity as areas of hydraulic fracturing induced seismicity. Areas following a random space temporal clustering model (Reeves South, Grisham West) indicate long-term SWD activity at several wells or short-term SWD or HF activity overlapping in time at many nearby wells.

For this mapping, Savvaidis et al., [85] performed a space-time, moving-window analysis of the observed seismicity to quantify whether nearby seismic events clustered in time around typical hydraulic fracturing job durations or occurred more uniformly in time. For seismic events within sliding, spatial disks of specified radius *R* and time windows *W*, they (1) determined interevent times *dt*, (2) sorted *dt* from smallest to largest, and (3) integrated the sorted *dt* to form a new event-time distribution function *F(t)* over the window *W*. They applied a one-sided (null hypothesis: F(t) not greater than uniform), Kolmogorov-Smirnov (KS) test of the fit of F(t) to a uniform distribution. Resulting KSdt statistics quantify whether the event times are perfectly uniform (interevent times all identical, KSdt=0) to randomly uniform (KSdt~0.35) distributed within the time window, as opposed to clustered on a time scale that is much less than the time window (KSdt→1.0).

Zones of high seismicity (earthquake density) (Figure 5) around Pecos (station PB02) and dense spatial clusters to the northwest (Grisham West) show random (Poissonian) event-time distributions (yellow-green), which, if the seismicity is caused by well activity, may indicate either long-term injection activity at several wells, or short-term injection or hydraulic fracturing activity overlapping in time at many nearby wells. Whereas further analysis of the Pecos area is hampered by the extremely high density of well activity and seismicity, the relatively isolated Grisham West clusters are good candidates for evaluating whether the seismicity is induced by long-term injection or multiple quasi-continuous hydraulic fracturing activities. The strongest KSdt space-time clustering (blue-purple) occurs southwest of Pecos in isolated and semi-isolated spatial clusters of seismicity (South Toyah, Reeves West, Jeff Davis Northeast and Jeff Davis East). These clusters are likely candidates for short-term, hydraulic fracturing -induced seismicity and are unlikely to be related to long-term injection activity. Lomax and Savvaidis [100] identified South Toya and part of Reeves West as areas where hydraulic fracturing was the probable causal factor of seismicity.

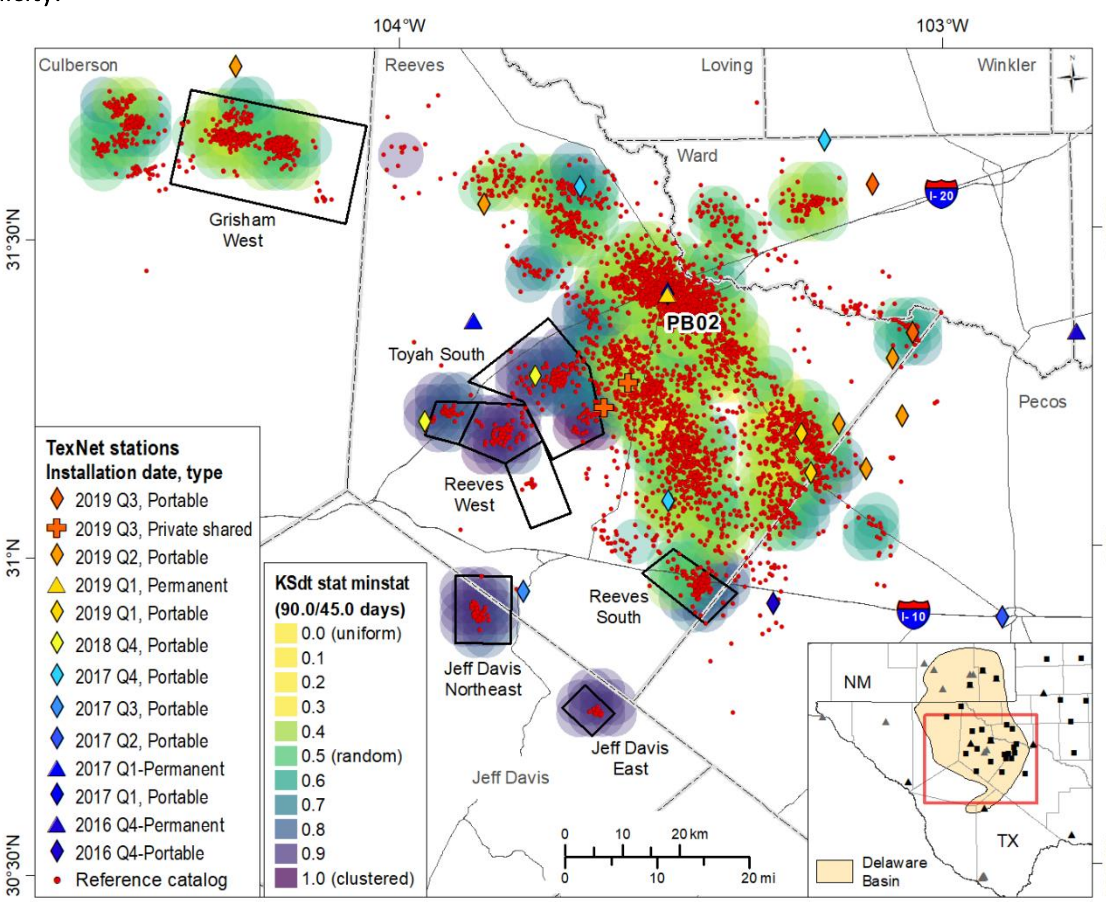


Figure 5 Map of minimum of Kolmogorov-Smirnov dt space-time clustering statistic in Delaware Basin using spatial disks of radius 4 km, sliding 2 km, and time windows of 90 days, sliding 45 days over period 2017.01–2019.11. Seismicity (red dots), seismic stations (diamonds and triangles), and names of cluster areas indicated. (Figure 2 from [85])

In addition, the same authors used a statistical model (Figure 6) to identify the association (likelihood) between an earthquake and a hydraulic fracturing or salt water injection well based on horizontal location between the well and the earthquake epicenter and the origin time of the event and the well-activity stop date.

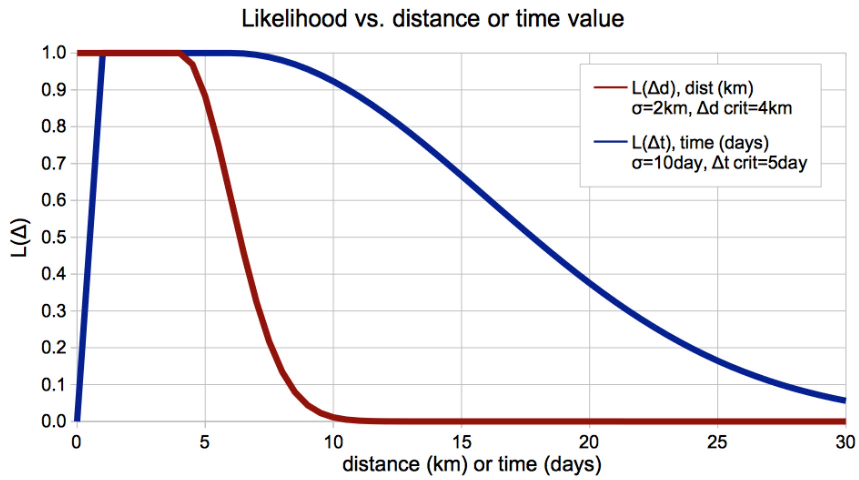


Figure 6 Likelihoods L(Δt), where Δt = difference between event origin time and real or estimated well-activity stop date, and L(Δd), where Δd = difference in horizontal distance between event and center point between toe and heel coordinates for hydrofracture job or well location for SWD. (Figure 3 from [85])

Although west Texas has a mixture of oil and gas operations, using the above two approaches Savvaidis et al., [85] have identified causality of seismicity, and presented earthquake induced by hydraulic fracturing (Toya South, Reeves West, Jeff Davis Northeast, Jeff Davis East) versus by wastewater disposal (Reeves South, Grisham West).

3.4. Seismic Hazard and Risk Assessment and Management

Although our survey of injection experience shows that the fear of induced seismicity is larger than the observed incidence and impact, it is important to evaluate and prepare for each of these risks in site selection and design so that they can be effectively managed. Risks of seismicity in CCS projects belong to three broad categories: 1) public perception and concerns, 2) damage to infrastructure at the injection site, and 3) damage to the subsurface in terms of CO_2 containment. There are published studies on risk assessment and management of CO_2 geologic storage approach which is also suitable for managing the risk of unwanted earthquakes [105].

Public perception ranks induced seismicity as a frequent and consequential concern about implementation of CCS. In a metadata review of 135 public perception studies on CCS [106], induced seismicity ranks in the top four, about equal to leakage risk and CCS effectiveness. Concerns about seismicity have caused a number of jurisdictions globally to put a moratorium on injection, with a motivation to stop hydraulic fracturing but a derivative impact also on CCS. The substantive risk that a project will be stopped, investment lost, and CO_2 emissions fail to be stored is likely the highest risk. We dedicate the last section of this report to examples of outreach practices that could mitigate this risk.

Damage to infrastructure is a focus of concern in any type of seismic event. Increased seismic hazard does not necessarily correspond to increased risk. A probabilistic seismic hazard assessment (PSHA) will provide the likelihood in an area of study the ground motion (Peak Ground Velocity, Peak Ground Acceleration, Macroseismic Intensity, etc.) exceeding a value. Usually, one would expect that the infrastructure used in CCS projects will not be affected and the likelihood of damage (risk) is minimal for a given small to moderate ground motion.

There are two main parameters here that should be considered as proactive measures: (a) site characterization, and (b) extensive monitoring at least six months prior to injection. The first one is important to safeguard that we select key sites that the likelihood of induced seismicity is minimal. Monitoring the state of stress during the site selection and continuously a few months prior to any human activity in the area of interest and onwards is important to secure the mitigation of seismic hazard during and shortly after the end of the CCS project.

In the case we have induced seismicity, an effective seismic monitoring program followed with an adaptive seismicity assessment should be able to identify any low magnitude induced seismicity that based on an adaptive risk mitigation plan should either decrease (in magnitude or rate of seismicity) or avoid migration to the CO_2 plume area.

Unfortunately, although, in some cases, it has been clear that injection close to the basement rooted faults, or when the maximum stress direction (SHmax) is close to the strike of existing fault zones, it is important to note that on a pre-stressed fault even small pore pressure changes can be the triggering mechanism for induced seismicity. However, both the process of effective pore pressure changes and the related induced seismicity need time to evolve to the first triggering event and also to a considerable hazard earthquake cluster. Monitoring is important in both cases, for the former, either as bottom well pressure and injection rates on a daily basis, and, for the latter, as efficient microseismicity monitoring.

Based on the above mentioned monitoring data, we can provide empirical physics-based relations [107] [108] or statistical assessments [85] that can help the operator manage the risk including mitigation measures, such as well completion design, limiting injection volumes/maximum injection pressures.

White and Foxall [9] provide the first comprehensive risk assessment of induced seismicity at CO_2 storage projects as they apply to US-based projects, expanding on concepts introduced by Pawar et al. [105]. In their assessment, they define as M1.5-M2 the lower magnitude of reported seismicity of concern that might trigger any risk management plan. Other regions of the world may consider this magnitude threshold too high. The same authors support the physics-based modeling approaches to help operators mitigate any hazard, keeping always in mind that pore pressure changes that might accelerate or de-accelerate seismicity have a significant delay. They relay conclusions similar to that derived by Majer et al. [109] on enhanced geothermal systems (EGS), in particular that a traffic-light system will fail if there is no precursor event ahead of a large earthquake, as highlighted by Muntendam-Bos et al. [110] and Baish et al. [111] from gas extraction experience in the Netherlands [112] or if operations have ceased at the time of the seismic event. Majer et al. [109] in the US developed a detailed right management framework asserted that any EGS project should be able to detect M1.0 or lower seismic events. Baish et al. [111] list the following criterions for traffic-light system to be efficient: “major” seismic events of increasing strength, each preceded by a series of smaller magnitude seismic events, on the one hand, and, on the other hand, sufficient mitigation measures that can be implemented quickly to have an impact before escalation to higher magnitude events.

A risk mitigation approach to the management of induced seismicity incorporating the vulnerability of infrastructure is presented in [113]. Authors support the development of an effective response plan for assessing induced seismicity, quantifying the risk, as the convolution of hazard, exposure, fragility, and consequence models. They consider that, in such models, uncertainties will be high, however, as the data from operation become available, an adaptive risk model will allow frequent updates of the risk model with less uncertainties. In such a workflow, the operator can have a starting mitigation plan that will be adjusted based on exceedance of the risk model and its uncertainties validated from observed data.

At a CCS site, the infrastructure of specific concern is wells and pipelines. Application of best practices for managing risks in case of damage, for example automatic shut offs, should need little adaptation for application to seismic risks. The unique properties of CO_2 because of its equation of state, for example Joule-Thompson cooling and the need for pipeline crack arrestor design should be considered, these risks are considered in other work on CO_2 infrastructure.

Damage to containment as a result of seismicity at a CO_2 storage site has been mentioned as a risk. However, the level of concern is disproportionate to the observed response to fluids in the subsurface. Many hydrocarbon fields are adjacent to faults in naturally seismically active areas. Subtle changes in gas flux has been proposed and used locally as a prospective “early warning” of changing state of stress. However, large scale loss of hydrocarbon containment has not been observed as a result of even very large seismic events. Any impact of induced seismicity on fault seal would likely be small and transient, based on this experience.

3.5. Current State of Induced Seismicity Modeling and Forecasting

The prediction of the earthquakes and their potential impact has been ongoing research [114]; [115]; [116]. The assessment of time-dependent earthquake hazard or earthquake forecasting generated with associated probabilities and errors is now the standard in earthquake predictability research. The methods of forecasting are mainly divided into the physical process models and the more general class of seismicity-based forecasting models [117].

The first method includes the models based on the assumption that the seismicity is acting as a sensor for the underlying physical process and can provide information about the spatial and temporal nature of that process (variation of the b-value, Load–Unload Response Ratio (LURR), Pattern Informatics index). The second method comprises from the models which characterize the physical spatio-temporal features of earthquake processes in a probabilistic manner, and then calibrate the model based on data available from seismic catalogs (epidemic-type aftershock sequence (ETAS), the Relative Intensity (RI) method). In this section we focus on the methods which have been used in the induced seismicity modeling and forecasting.

The seismic-hazard forecast for the central and eastern United States from induced and natural earthquakes has been presented in [118], [119] for the years 2016 and 2017. The zones of induced seismicity studied in this research is presented in Figure 7. The map shows the locations of oil and gas plays and sedimentary basins in relation to wells that have been associated with induced seismicity according to U.S. Energy Information Administration [120] and Weingarten et al. [121] and were investigated in this study.

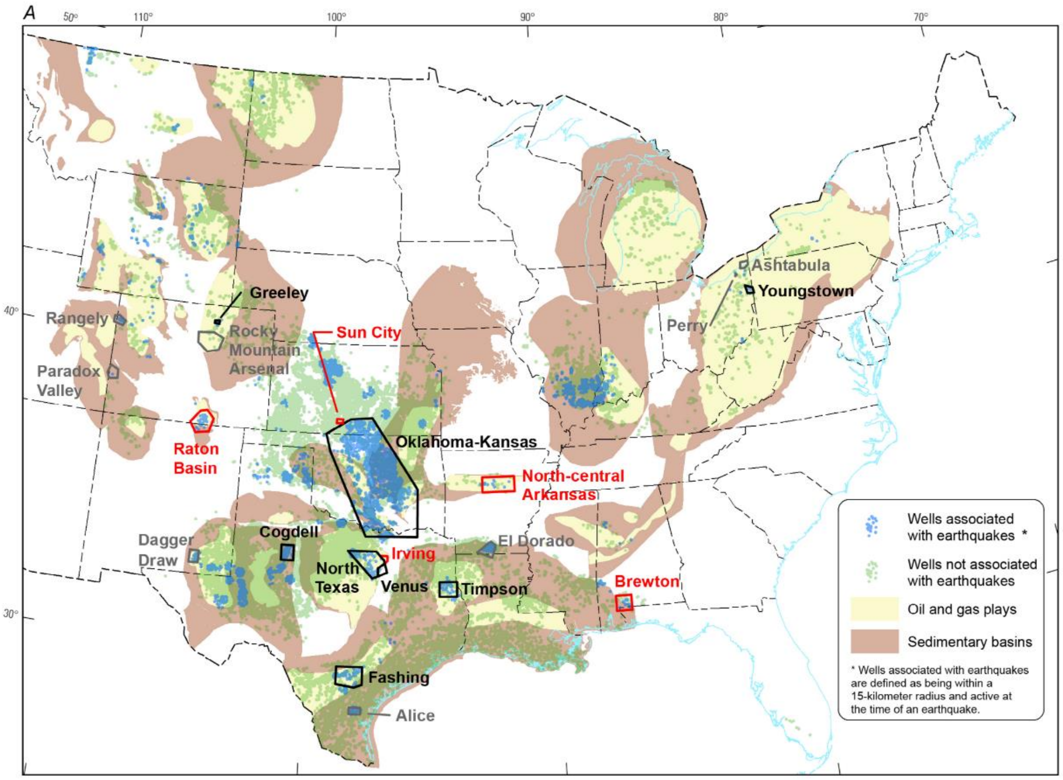


Figure 7 Zones of induced seismicity defined in [118]

Using logic trees (see Figure 8) for one-year seismic hazard model, the model that [118] used, assumes that earthquake rates calculated from several different time windows will remain relatively stationary and can be used to forecast earthquake hazard and damage intensity for the year 2016. This assessment is the first step in developing an operational earthquake forecast for the CCUS, and the analysis could be revised with updated seismicity and model parameters. The levels used in the logic tress for sites within induced zones and presented in Figure 8. In detail, Level 1 describes an earthquake catalog that extends to the end of 2015 and fault and area sources from the 2014 National Seismic Hazard Model (NSHM) [122], [123]. Level 2 describes the classification of earthquakes as induced or natural and the estimation of earthquake rates. Level 3 describes the durations of the earthquake catalogs that best predict earthquakes. Level 4 describes the smoothing parameters applied in the model. Level 5 describes the maximum magnitudes applied in the model. Level 6 describes the alternative ground motion models [118]. The outcomes of the forecast earthquake hazard and damage intensity from this study are shown in Figure 9.

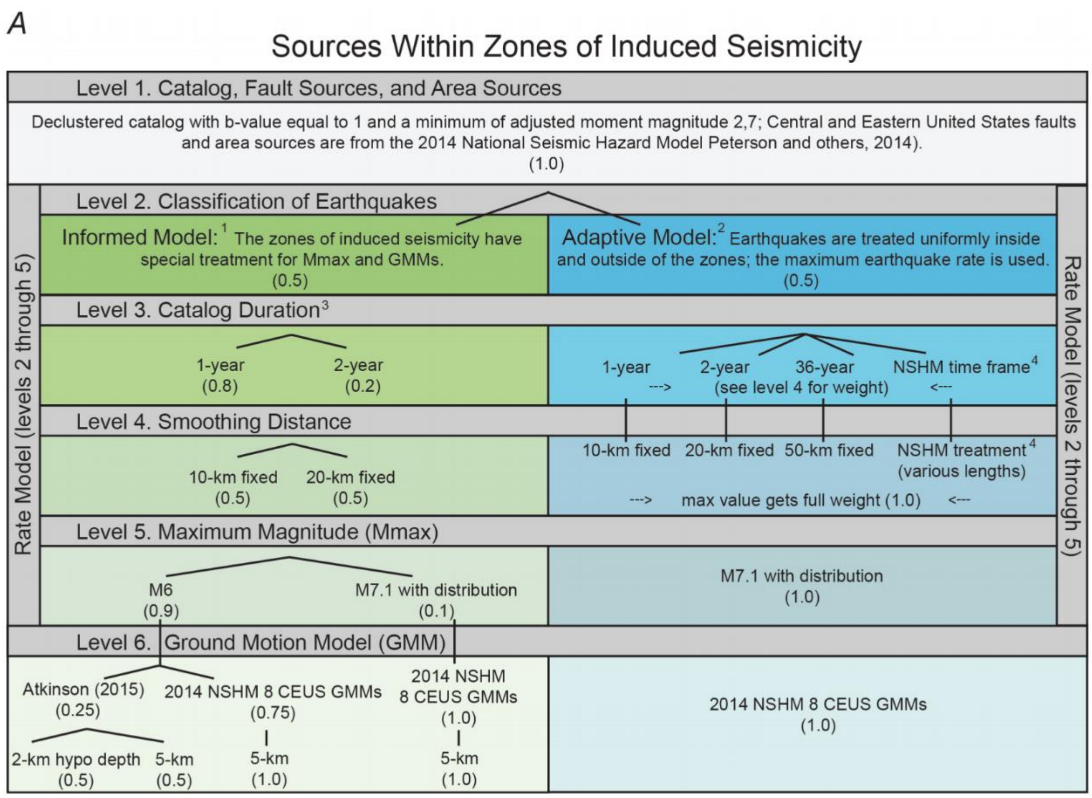
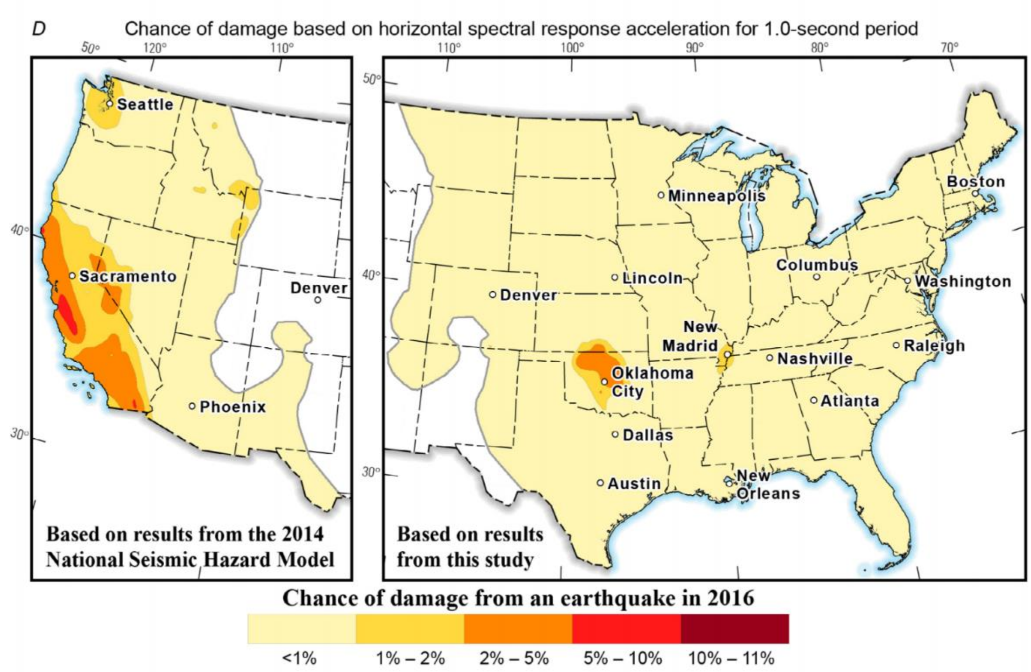


Figure 8 Two logic trees in the 2016 one-year seismic hazard model presented in [118]



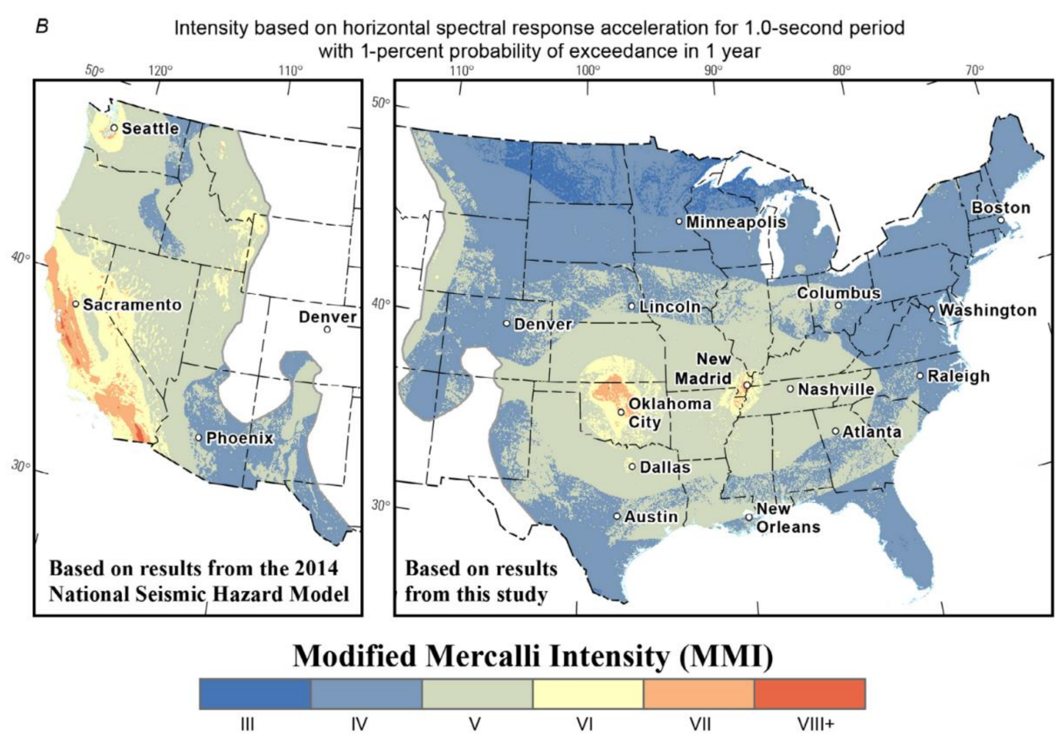


Figure 9 Modified Mercalli Intensity maps and chance of damage for the Western United States and the Central and Eastern United States (CEUS) based on 1-hertz spectral acceleration presented in [118]

A physics-based forecasting of induced earthquakes hazards in Oklahoma and Kansas has been studied by Langenbruch C. et al. [124]. This model forecasts the probability of damaging induced earthquakes in space and time by using a hybrid physical–statistical model, where the seismicity is driven by the rate of injection-induced pressure increases at any given location and spatial variations in the number and stress state of preexisting basement faults affected by the pressure increase [124]. The method they used is to collect injection well data from the areas under investigation and develop a three-dimensional hydrogeologic model which simulates fluid injection from wells operating in the area for twenty years using a finite difference numerical code developed by the U.S. Geological Survey (MODFLOW). The model they used to compute the probability of triggering M ≥ 3 earthquakes is calculated from the divide of the histogram of pressure rates triggering observed earthquakes by the histogram of monthly pressure rates at the seed points in the model. Using this model, they calculate the 1-year maps of the seismic hazard to assess the probability of potentially damaging induced earthquakes in Oklahoma which is shown in Figure 10. Langenbruch C. et al. [124] found that earthquakes observed in the year of the predictions occur where the calculated model in this study forecasts enhanced exceedance probabilities.

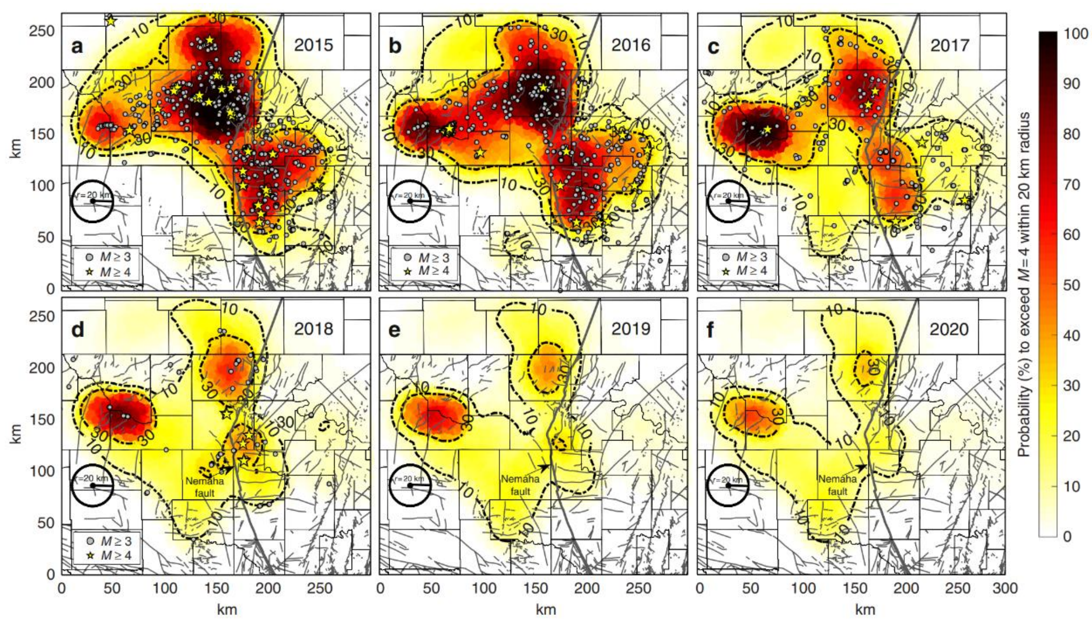


Figure 10 Physics-based 1-year magnitude (M ≥ 4) exceedance probability forecasts (2015–2020). Exceedance probabilities are forecasted in areas of 1257 km2 (20-km radius) and for the time of 1 year presented in [124]

A semi-empirical model which uses statistical and hydromechanical modeling to identify the seismicity rate forecasting in Oklahoma has been adopted by Grigoratos et al. [108]. The methodology which is followed in this study simulates the observed seismicity in space and time, given the injection history. Authors adopted a model dealing with the magnitude-frequency distribution when fitting a b-value to forecast large magnitude rates. The model predicts a linear relationship between the number of induced events and the injected volume. The advantages of this model underlined by [108] is that it captures well the magnitude–frequency distribution over the entire magnitude range of interest and is consistent with the “historical” tectonic rates (see Figure 11).

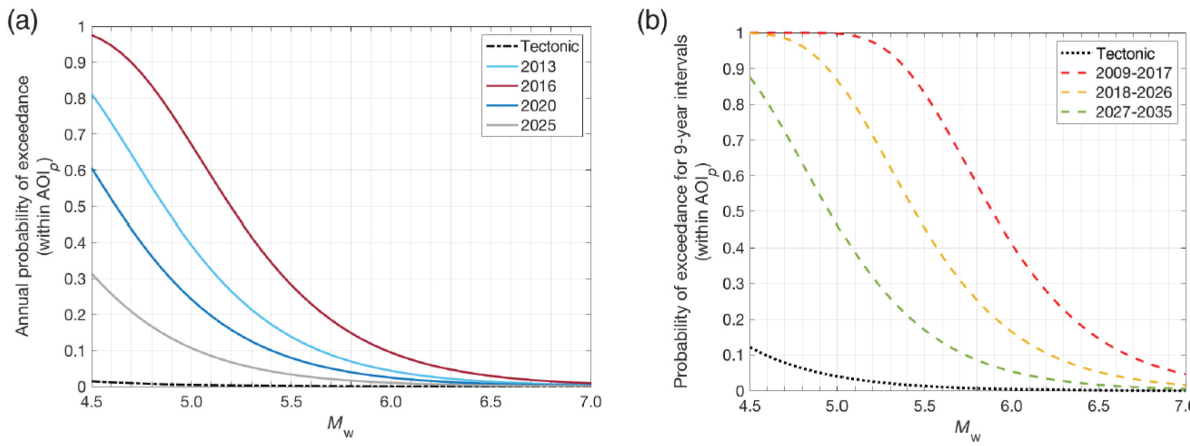


Figure 11 Magnitude exceedance probabilities within the area of interest (AOI_p)for different time periods. (a) Annual exceedance probabilities and (b) probabilities over 9 yr time periods. The model calibration included data through December 2017 [108].

Additional methods:

The variation of the *b*-value relation with seismological observations has been studied extensively over the last twenty years [125]; [126]; [127], [128]; [129]; [130], [131]). Studies are supporting the observation that the *b*-value is linked to the differential stress [132]; [130], [133] where it has been shown that the stress drop designates the difference in shear stress on the fault plane before and after the earthquake (e.g., [134]). The *b*-value is defined as the slope in the Gutenberg-Richter power law distribution and is expressed as $\log_{10}N= a-bM$, where *N* is the cumulative number of events, *M* is the earthquake magnitude, and *a* describes the productivity.

Models have established a link between the seismological observations and the geomechanical properties of the source region by observing that the less critical stress states result in lower stress drops and higher *b*-values. One should note that the site characterization is the identification of the geological and mechanical properties of the site through geomechanical assessment in order to ensure safe operation [11]. Geomechanical modeling is of high importance for large-scale geologic storage projects located across diverse geologic and regional settings. It is advancing by integrating the correct physical properties of the earth (critical stress, strength of formations, fault slip potential, porosity, etc.) with the measured data (injection volumes, pressures or rates, seismic moment, Coulomb stress etc.), see Table 3. Pore pressure and stress changes for an earthquake cluster can be computed, and the sensitivities of the model parameters can be analyzed. In this way we can better understand the physical mechanisms related to occurrence of induced seismicity (triggering and poroelastic response). The modeling tools which are used to estimate the hazard and risk forecast, so that it can be proactively avoided, are combining seismology and numerical modeling and examine their application to geothermal energy production.

Table 3 List of physical properties and measured data that can support advanced geomechanical modeling and associated tool/method for collecting the needed data.

Physical properties	**Tools/methods currently being used for collecting the data**
coulomb stress change	fault geometry, slip, coefficient of friction
coulomb stress failure	shear stress (stress inversion using fault geometry), vertical stress (geology), pore pressure, coefficient of friction
strength of formations,	uniaxial (unconfined) compressive strength is the standard strength parameter of intact rock material.
fault slip potential,	probabilistic analysis of fault slip potential
compressional and shear velocity	well logs, seismicity, earthquake tomography
porosity	cores, well logs
Measured data	
injection volumes,	provided by operator
pressures	bottom hole pressure measured by an instrument
seismic moment	Full waveform moment tensor inversion, source spectra (recorded waveform data of an earthquake)
coulomb stress	Slip model
fault plane	full waveform moment tesnor inversion and additional data (surface wave inversion, double difference relocation)
spatio-temporal earthquake migration	seismicity with accurate earthquake location
stress drop	recorded waveform data of an earthquake

Recent studies evaluate the seismic hazard through the constraint of the magnitude of the largest expected earthquake during a future time interval [135]. This is achieved by the combination of the Bayesian methods with the extreme value theory and the assumption that the occurrence of earthquakes can be described by the statistical model of the Epidemic Type Aftershock Sequence (ETAS) process. The Bayesian statistical methods can be used to provide a suite of approaches to analyze statistical aspects of seismicity and to compute predictive distributions of seismicity by studying past seismicity. The statistical model based on ETAS hypothesis [136] describe the spatio-temporal distribution and features of actual seismicity [137]; [138]; [139], [140]; [141]; [142]; [143], [144]. In general, the ETAS algorithm is used in a branching model, where the parent event of a given magnitude and locations produces a series of child events that occur within some specified region and time. The average number of children produced for every parent event is the branching ratio [145]. The ETAS model includes the contribution of every previous event based upon the magnitude of the triggering earthquake, the spatial distance from the triggering event, and the time interval between the triggering event and the time of the forecast.

The relative intensity (RI) forecast model is used to predict the total number and frequency-magnitude distribution of future seismicity. This model is monitoring the seismicity in real time with multiple statistical forecast models and then the probabilities of exceeding a ground motion intensity level in order to translate the forecast to seismic hazard [146]. The forecast models are based on data sets which give information about the activity and recorded seismicity in a given time window. The activity rate is the parameter that can be controlled by the operators so these models are providing thresholds which cannot be exceeded by the decision makers by converting into time-varying probabilities of exceeding various intensity levels. Based on the Omori-Utsu law of aftershock decay and the Gutenberg-Richter law of frequency-magnitude distribution, the seismic hazard can be forecasted based on seismicity catalogs [147] [148].

Another leading edge of research and innovation in forecasting of seismicity is COSEISMIQ (http://www.geothermica.eu/projects/coseismiq/) project (COntrol SEISmicity and Manage Induced earthQuakes) where seismology and numerical modelling is used to improve the Adaptive Traffic Light System applied to geothermal energy production, and provide a hazard and risk forecast. This project aims to implement innovative tools for the management of the risks posed by seismicity. This is achieved by a combination of the seismic monitoring and ambient noise imaging, geomechanical models and risk analysis methods. These technologies are aiming to be used as a data-driven, adaptive decision support tool during industrial applications.

4. Permitting and Regulatory Oversight on Induced Seismicity

In areas of increased injection induced seismicity, the regulatory authority has defined rules and expectations for permitting, incorporating in most cases, past earthquake data (distance of seismicity from the well and magnitude of events) and characterization of subsurface hazards. In some cases (Canada, Oklahoma, Ohio, UK), the operator has to follow a traffic light system that "controls" its actions and provides guidance on risk mitigation based on an earthquake magnitude threshold, which is, in most cases, different for each country or state. In some cases, the operator has to provide to the regulator a risk mitigation plan to be followed if the threshold magnitude value is exceeded. All those geographically-based cases are presented below and evaluated to describe the regulatory environment of induced seismicity risk, and define best practices for risk mitigation and minimizing earthquake resilience.

We consider any adaptation needed for translating very dense data from key study areas such as the Geysers and other data cited by the prior review by IEAGHG R&D programme [58]. From this analysis, we inventory the choice points and regulatory oversight procedures that either have been made by existing regulations or are options to be considered for future regulation. They illustrate the regulator thinking to assure that best practices are followed with regard to effective management of seismic risk at future CCS sites, both during site selection, and in design and interpretation of seismic monitoring data. In the following sections, we review the regulatory frameworks available through various entities and regulatory authorities.

We have to note here that we are aware of other jurisdictions and differences in attitudes to induced seismicity at countries such as Netherlands, Germany and the Canton of Jura in Switzerland where permitting and regulatory oversight on induced seismicity is arguably more advanced. For example in the Netherlands the government has stipulated that "safety risks should be explicitly analyzed in mining companies' production plans". So the State Supervision of Mines (*Staatstoezicht op de Mijnen* = SodM) is charged to develop a temporary guideline for analyzing risks as a result of earthquakes induced by gas production [149] ahead of a definitive guideline on seismic hazards that is to be developed by operators and research institutes. In next sections, we will elaborate more about the regulatory framework in Switzerland, the Canton of Jura.

4.1. USA:

The underground injection of fluids is regulated in the United States by the U.S. Environmental Protection Agency (EPA) under the Safe Drinking Water Act (subpart of Underground Injection Control or UIC). Because of the fragmented nature of US environmental law, federal oversight of induced seismicity under this law is limited and regulations are handled at the state level. The following elements typically need to be evaluated during the permitting process:

- The geology of the proposed injection site
- The technical specifications related to the well integrity
- The injection pressure and
- The zone that the injection occurs below the zone of fresh water

The six categories listed by EPA on injection wells are given in Table 5 of the Appendix. As shown in this Table the injection of geothermal fluids is handled by Class V wells while the injection of oil and gas by Class II injection wells. According to EPA, there are currently more than 172,000 Class II wells permitted in the U.S. Non-EOR CO_2 storage wells belong to Class VI, of which two permitted wells are operating, 4 are permitted but not drilled, all in Illinois. The operators of these permits negotiated a high quality monitoring program, setting a precedent. A number of projects funded by US DOE under the Carbon SAFE program are bound to obtain Class VI permits. The interaction with EPA on expectations to manage CO_2 injection in tandem with evolving state programs that provide oversight of injection and induced seismicity risk described in following paragraphs will be important for large-scale implementation of CCS.

Arkansas

In Arkansas, oil and gas activity and Class II injection are regulated by the Arkansas Oil and Gas Commission (AOGC) General Rules [150]. The rules allow the AOGC to identify and designate appropriate areas for injection disposal activities and implement a moratorium if deemed necessary. This aims to protect drinking water sources and promote the conservation of state oil and gas resources. The rules also require that operators of existing Class II wells within an area which has been subject to earthquakes, need to submit bi-weekly reports to the Commission to report the daily injection volumes and the maximum daily injection pressure.

The Enola and the Guy-Greenbrier earthquake swarms, which were associated with injections of wastewater from shale gas production, were the cases from which stemmed the AOGC response to impose a moratorium on new disposal wells in 2010.

In 2011, the AOGC revised the rules for Class II wells and established a permanent moratorium zone around the major fault systems in the sensitive areas.

- The state prohibited new disposal wells and required plugging of four existing wells within the moratorium zone.

- The rules required the approval of the commission and a public hearing before any Class II well can be drilled within determined distances from the so-called Moratorium Zone Deep Fault or a regional fault.
- Class II wells proposed for disposal above or below the Fayetteville Shale formation are subject to new requirements. These requirements included well siting and spacing, and permit applicants providing information with regards to the area structural geology.
- Installation of flow meters and daily information about the injection volume and pressure information at existing disposal wells were required.
- In parallel to all the new rules the State installed additional seismic monitoring equipment in order to act as an early detection and warning of the seismic activity.

California

The California regulations follow the California Code Regulations [151] which requires operators to monitor the California Integrated Seismic Network from the time they begin hydraulic fracturing of a well until 10 days after they have finished fracturing.

The Alquist-Priolo Earthquake Fault Zoning Act (1972) which was signed into California law in order to mitigate the hazard of surface faulting to structures for human occupancy, along with the Seismic Hazards Mapping Act (1990) guide the regulatory at the "Zones of Required Investigation" in California. Their main goal is to give information to the public for their safety and to minimize the loss of life and property caused by earthquakes. The cities which are included in these zones must regulate certain development projects within them. The California regulations follow the California Code Regulations [151] and Article 4 “Underground Injection Control”, which require operators to monitor local seismicity from the California Integrated Seismic Network from the time they begin hydraulic fracturing of a well until 10 days after stimulation completion.

California regulations are focused on two main requirements regarding injection data from wastewater injection wells:

- Injection well permit applications must include an injection plan, including a statement of the primary purpose of the project, a map showing injection facilities related to the project, a statement of the anticipated project duration, the identification of all wells that are part of the underground injection project, a monitoring system, including methods or standard operating procedures, and the method of injection and identification of the source(s) of the injection liquid.
- The operator shall undertake remedial work or conduct further testing as necessary to satisfy the Division that the well will not damage life, health, property, or natural resources.

Colorado

In Colorado, oil and gas activity and Class II injection wells are regulated by the Colorado Oil and Gas Conservation Commission and the code adopted is the Colorado Code of Regulations [152]. In 2011, the Commission included a seismicity review in its evaluation of applications for Class II injection well permits. Also, the Commission collaborates with the Colorado Geological

Survey and the U.S. Geological Survey earthquake database in order to evaluate the potential for seismicity. If there has been past seismicity in the vicinity of the proposed injection well location, the Commission requires the permit applicant to use geological data to define the fault reactivation potential before approving the application.

Illinois

The Illinois Department of Natural Resources (DNR) regulates the oil and gas industry and has primary authority to regulate oil and gas activities in the State, with the aid of the Illinois State Geological Survey, Illinois State Water Survey, State Fire Marshal, and the Illinois Environmental Protection Agency [153]. The Hydraulic Fracturing Regulatory Act, was adopted in June 2013. It applies to all high-volume hydraulic fracturing operations that use more than 80,000 gallons (~303,000 litres) of hydraulic fracturing fluid per stage or more than 300,000 gallons (~1,136,00 litres) of hydraulic fracturing fluid total on wells drilled at least 100 feet (~30.5 m) horizontally. In November 2014, Illinois adopted regulations implementing the Hydraulic Fracturing Regulatory Act.

The Illinois regulations apply to "all Class II UIC disposal wells that inject any Class II fluids or hydraulic fracturing flowback from a high volume horizontal hydraulic fracturing operation permitted by the DNR under the Hydraulic Fracturing Regulatory Act" [153]. According to the "traffic light" system, the DNR notifies Class II UIC well permittees within a certain radius of the epicenter of seismic activity of an alert. This alert indicates that, as the magnitude of an earthquake increases, the Class II UIC well permittees are notified. These notifications are stated to as "green light," "yellow light," and "red light" alerts, depending on the magnitude of earthquake. If a well activity is suspected of having triggered induced seismicity, the regulations give the authority to the DNR to require the Class II UIC well permittee to implement seismic monitoring. Also, the DNR may issue a pause order in all wells that receive a red light alert and are within 6 miles (~9.7 km) of the epicenter of the earthquake. Wells that receive a pause order must meet with the DNR and the Illinois State Geological Survey and provide well data for the last six months. This way a settlement agreement is implemented that includes induced seismicity mitigation measures [153].

Kansas

The Kansas state with the State Action Plan on 2015 [154] funded a permanent network of seismometers in order to allow Kansas to detect and locate earthquakes with a magnitude 2.0 or greater. The Action Plan recommended that Kansas fund a portable seismic array that could be deployed to areas experiencing seismic activity so that more detailed information regarding seismic events could be obtained. Also, the Action Plan suggested a scoring formula. When seismic events exceed a specified score, the Kansas Corporation Commission can issue an order requiring increased monitoring. This formula is described with the seismic action score (SAS) by adding the numeric value of the square of the magnitude of an earthquake to the sum of the individual weighted scores for each of the variables listed in Table 4 Seismic scores.. [154].

$$SAS = Magnitude^2 + Score_{felt} + Score_{structure} + (2 \times Score_{number})^2 + Score_{local\ recursion}{}^3 + Score_{recursion\ regional} + Score_{recursion\ time}$$

Table 4 Seismic scores.

	Risk Variables		Clustering Variables			
Score	**Felt[1]**	**Usable Structure[2,3]**	**Additional Number in Past 30 days[3]**	**Localized Natural[4] Recursion[3]**	**Regional Natural[4] Recursion (Kansas Database[5])**	**Additional # of Events[3] +/- 0.5 Magnitude Over +/- 24 hrs**
0	No	No	0	yes	yes	0
1	Yes	Yes	1	no	no	1
2			2			2
3			3			3
4			≥4			4

1 *Based on USGS "Did You Feel It" web site or credible reports*
2 *Based on aerial mapping or field observation of man-made features that can be safely occupied by humans*
3 *Within a 6 mile radius*
4 *Natural from the axiom, for every 100 magnitude 1 seismic event there will be 10 magnitude 2s and 1 magnitude 3 seismic event*
5 *Kansas database includes all earthquakes recorded in Kansas since the 1970s by KGS, USGS, or OGS*

The 2015 order [155] specifies that operators of injection disposal wells located in certain areas of the Arbuckle formation need to measure daily injection volume and pressures, and to report monthly the daily figures of the Area of Interest.

Oklahoma

In Oklahoma, oil and gas activity and Class II injection wells are regulated by the Oklahoma Corporation Commission through the Commission's Oil & Gas Division. Underground Injection Control in Oklahoma is governed by the following regulations: Oklahoma Administrative Code Underground Injection Control [156] and Oil & Gas Conservation [157]. The Commission's regulations generally require that operators of disposal wells record injection volumes and pressures on a monthly basis.

The "traffic light" system was first put in place in 2013 in response to the concerns over the possibility of earthquake activity being caused by oil and gas wastewater disposal wells in Oklahoma. It has been in a state of constant evolution since then, as new data becomes available [158].

The traffic light system for Oklahoma includes [158]:

The "yellow light" permitting program that requires seismicity review for any proposed disposal well and requires special permitting based on seismicity concerns for:

- Any well proposed within three miles (~4.8 km) of a stressed fault, even in the absence of seismicity
- Any well proposed within ten kilometers (~6.2 miles) of an earthquake "swarm" or magnitude 4.0 event
- Increase the required recording of well pressure and volume for any existing Arbuckle well in the state from monthly to daily.

- Rules requiring Mechanical Integrity Tests for wells disposing of volumes of 20,000 barrels a day or more have increased from once every five years to every year, or more often if so directed by the Commission
- Full review of disposal well operations in an Area of Interest

In addition, the Oklahoma Corporation Commission developed a new system of protocols for industry to follow regarding quake detection in December, 2016. The new rules make these procedures stricter. Key changes include:

- Operators are required to have access to a seismic array that gives real-time information on earthquakes
- Mitigation actions must occur at detected magnitude levels of 2.0, smaller than the earlier 2.5 magnitude.
- Some operators will need to pause operations for 6 hours when a magnitude of 2.5 is felt, smaller than the prior reading of 3.0.

Ohio

In Ohio, oil and gas activity and Class II injection wells are regulated by the Ohio Department of Natural Resources Division of Oil & Gas Resources. Deep injection wells and produced water in Ohio are governed by the following regulations: Ohio Administrative Code [159], [160] and Ohio Revised Code [161]. The Division may require pressure fall-off testing, investigation of potential faulting within the immediate vicinity of the proposed site of the injection well, tracer or spinner surveys, and various logs and may require the operator to submit a plan for seismic monitoring [162]. Also the regulation states that all injection wells permitted after the effective date of the amendment must be "continuously monitored using a method acceptable to the chief" of the Division and it requires that operators would install a device that will automatically shut off the injection well if injection pressures exceed the maximum pressure allowed by the permit for that well [162].

Texas

In Texas, oil and gas activity and Class II injection wells are regulated by the Railroad Commission. The Texas Railroad Commission adopted the following regulations, effective on November 2014:

- Texas Administrative Code (TAC) 3.9 (Statewide Rule 9) [163]for disposal into formations that are non-productive of oil, gas, or geothermal resources.
- Texas Administrative Code (TAC) 3.46 (Statewide Rule 46) [164] for injection or disposal into formations that are productive of oil, gas or geothermal resources.

These codes specify that [164]:

- Any entity applying for a permit for a new injection well to dispose of saltwater or other oil and gas waste must include with their application information from the U.S. Geological Survey seismic database regarding historical earthquake activity in a 100-square-mile (259 km^2) area around the proposed injection site (a circle with an area of 100 square miles would have a radius of approximately 5.64 miles or 9.08 kilometers)

- The Commission staff has the authority to modify, suspend, or terminate a disposal well permit if scientific data indicates that a disposal well has been determined to be contributing to seismic activity or is likely to be determined to be contributing to seismic activity
- The Commission staff may ask operators to report injection volumes and pressures on a more frequent basis than the annual basis otherwise required if conditions exist that increase the risk that fluids will not be contained in the "injection interval,"
- The Commission staff may require that an applicant for a new injection permit submit information, "such as logs, geologic cross-sections, pressure front boundary calculations, and/or structure maps, to demonstrate that fluids will be confined to the injection interval"

4.2. Canada

The British Columbia Oil and Gas Commission (BCOGC) and the Alberta Energy Regulator provide the regulatory oversight of disposal wells in their respective provinces in Canada. According to regulations, the operators are required to monitor the seismic activity at their operating sites and complete detailed risk assessments. In parallel, they need to submit a response plan to the regulator if operations trigger a seismic event. The details of the regulations are presented in the two following sections.

Alberta

Alberta Energy Regulator is the regulator of energy development in Alberta—from application and exploration, to construction and operation, to decommissioning, closure, and reclamation. In 2015 the Alberta Energy Regulator-Subsurface Order No2 [165] applied specifically to the Duvernay Zone the Induced Seismicity Traffic Light Protocol where the "green light" is referred to earthquakes with magnitude less than 2, the "yellow light" referred to earthquakes with magnitude more or equal to 2 and less than 4 and "red light" alerts referred to earthquakes with magnitude more or equal to 4.

British Columbia

The British Columbia Oil and Gas Commission (BCOGC) provides in depth regulatory oversight of disposal wells to ensure wellbore and formation integrity, safe operation and the containment of disposal fluids [166].

In 2016 the new permit conditions required ground motion monitoring within two specified areas in NE British Columbia [167]. These permit conditions include [166]:

- Deployment of at least one Class A, strong motion sensor within 3 km of the drilling pad.
- Mandatory monitoring during all injections, encouraged during flow-back

- Report any occurrence of > 0.008g
- Ground shaking, plus waveforms in SEED format

The 2017 Amendments to the Drilling and Production Regulation of the Oil and Gas Activities Act [168] specified that seismicity monitoring is required for all injection operations (not just hydraulic fracturing and waste water disposal).

In 2018 a new order is issued on monitoring, mitigation, and reporting requirements for permit holders in the Kiskatinaw area [169]. These orders include:

- Deployment of at least one Class-A strong-motion sensor within 3 km of the drilling pad
- Suspension of operations for any magnitude 3 events
- Initiation of mitigation plan for any magnitude 2 events
- Inform BCOGC for any magnitude 1.5 events

4.3. UK

Regulatory roadmap for UK was published by the Department of Energy and Climate Change (DECC). The roadmap contains the requirements for the licensing, permitting and permissions process for onshore oil and gas exploration. In addition, it aims to help operators understand the regulation process for onshore oil and gas exploration. UK operators are instructed to follow some minimum standards in a continuous effort for improvement.

In February 2013, the United Kingdom Onshore Operators Group (UKOOG), the representative body for UK onshore oil and gas companies, published industry guidelines covering best practice for shale gas well operations in the UK.

Best practice guidance, which has been adopted by DECC, is set out in the Report by the Royal Academy of Engineering [170]. It is recommended that traffic light monitoring systems should be implemented and data fed back to well injection operations so that action can be taken to mitigate any induced seismicity [170].

4.4. Switzerland, Canton of Jura

The regulatory approach taken in Switzerland (particularly the Canton of Jura) is highly advanced. The regulator’s permit for a geothermal, (engineered geothermal system or EGS), project includes 63 conditions where 21 conditions are for induced seismicity. [171] [172]

Generalities (3 specific rulings): strict adherence to Environmental Impact Assessment; evaluations and comments of the Swiss Seismological Service to be incorporated:

Monitoring of naturally occurring and induced seismicity (5 specific rulings): permit to install microseismic observation network independent of permit to explore & develop geothermal resource; 6 months of background monitoring according to guidelines set by the Swiss Seismologicall Service; real-time, automated & data publically available; velocity model updated using best available technology;

Insurance coverage (2 specific rulings): Fr. 80 Million insurance coverage; evidence must be systematically collected;

Hydraulic stimulation operations (6 specific rulings): employ Traffic Light Systems (*TLS*) and Adaptive TLS (ATLS), independent expert group, assessment of statistical measures of earthquake catalogue («b-value»); specific guidelines, for example, if seismicity cloud maps out a lineament, immediate stop;

Update risk analysis (4 specific rulings): 1:1 million probability of fatality must not be exceeded; new information requires update; group of experts to be involved; if potential damages exceed Fr. 64 Million, revise guidelines;

Procedure in the event of an earthquake greater than the expected threshold of the first damage (1 specific ruling): stop.

Whether or not rulings should rely on advanced, yet unproven, concepts such as sophisticated forecasting tools (a subject of intense research & innovation) is an interesting discussion.

5. Outreach Methods and Processes

Attaining and maintaining social license to operate is widely recognized as a key element to site and operate a CCS project. Concerns about induced seismicity is part of the portfolio of assurances that might have to be managed, partly because of perceived overlap with hydraulic fracturing [173]. Much of what has been written about SWD seismicity is generally applicable to CCS seismic concerns as well [174]. Information provided by trusted parties and transparency remain important elements for a positive resolution of any conflict. Skills in dealing with causality, magnitude of events, depth of events, and the probabilistic aspects of earthquake prediction remains challenging in the context of concern about seismicity.

The outreach activities aim mainly to foster a positive engagement of the public and accurate reporting of the issues raised from the different sectorial activities (geothermal, oil and gas, CCS etc.). Responding to a seismic event can be similar to any emergency response and, for this reason, a communication plan needs to be established and proactive outreach and education strategies need to be part of the planning process. These strategies mainly include use of digital and social media, public events and meetings, and education of key audiences [175]. Some representative examples of outreach activities are presented in the following sections.

Enhanced Geothermal System (EGS) projects and the Newberry Geothermal Energy (NEWGEN) Frontier Observatory for Research in Geothermal Energy (FORGE) site [176]:

The public outreach efforts for this federally-funded Enhanced Geothermal site in a volcanic area of Oregon are focused on maintaining an up-to-date online presence through a blog, a website and a Facebook page. The NEWGEN Communications and Outreach Plan was created to inform stakeholders about EGS, induced seismicity, NEWGEN, and FORGE. It also underlines the advantages that EGS embraces and discusses about the concerns related to the safety. On the other hand, it also highlights the benefits to the community and region of locating FORGE at the NEWGEN site. In addition, the outreach efforts include local events such as field trips by University students which significantly improve the community support for the project.

After the end of field operations, the results of the operations in NEWGEN are presented to the public and other stakeholders through web sites, social media, press releases, peer-reviewed publications, public outreach meetings, and reporting. In parallel to the public outreach, the government communications are achieved by frequent regulatory and technical communications and laboratories continue throughout the project, with increased frequency during field site activities. Also, according to the NEWGEN an Induced Seismicity Mitigation Plan, event-specific communications in response seismic events are carried out based on defined magnitude threshold values.

Tomakomai CCS Demonstration Project

The Tomakomai CCS Demonstration Project was conducted with the understanding and support of the local government, industries and local community. The outreach activities for this project included [177]:

- Panel exhibitions held in Tomakomai and nearby cities, as well as other cities in Japan
- CCS forum held annually for Tomakomai citizens since 2011; typical attendance ranging from 300 to 400 people
- Site tours of facilities and observation wells open to general public
- Information disclosure system: disclosure of CO_2 injection volume, borehole pressure and temperature, seawater CO_2 concentration, earthquake and micro-seismicity data on Japanese CCS website
- Mini seminars for students held in universities in Hokkaido as well as nationwide
- Kids' lab classes in primary and secondary schools in Tomakomai to enhance understanding of global warming and CCS through CO_2 experiments. Site tours for children.

A test of the outreach program for this project occurred in response to public official concern about this project involvement in the 2018, magnitude 6.7 Hokkaido Easter Iburi Earthquake. The effective response to this concern by the project team provides a valuable example for other projects [28].

Alberta Energy Regulator:

The Alberta Geological Survey (AGS) encourages their staff to engage members of their professional communities and attend conferences and workshops where they make presentations and display posters dealing with aspects of the geology of Alberta. It also reaches out to schools, teachers, and the general public. The AGS website offers a selection of photographs, posters, maps, and presentations about the geology of Alberta meant for a general audience, and a compilation of links to geoscience related websites, including geoscience education and reference sites.

In addition, providing extended communication and educational outreach is an objective of many Geological Surveys. A continual challenge is to engage the public beyond the technical client. Conversion of 3D geological model into games and application of virtual and augmented reality, and use of 3D printing technology to transfer knowledge to a wider group of audience is also by geological survey such as British Geological Survey [178].

Calpine Geothermal Visitor Center Upgrade Project- The Geysers in California

An example of strengthening the engagement with the public and the outreach activities in the Geysers geothermal field was the development of the Calpine Geothermal Visitor Center in Middletown, California in 2001 [179]. This visitor center consists of displays presenting the history and geology of The Geysers. It also provides interactive displays designed to educate the visitors about key issues and benefits of geothermal energy. In addition, exhibits have been created to examine sustainable energy options and present the challenges and the potential of enhanced geothermal systems (EGS). The exhibition also provides videos and displays which highlight the key components of drilling technologies.

6. Concluding Remarks and Recommendations

There is a perception that induced seismicity will occur in some storage project associated with CCS. The reason is that, in the fractured brittle crust of the earth, triggering existing or new rupture zones is an expected response to changes in the local stress and pore pressure via injection. However, the susceptibility of the Earth's crust, to injection triggering any induced seismicity as well as the potential for ground motion to have any impact, vary greatly. The data presented in this report provides us the opportunity to recommend approaches to managing this risk.

In the past 15 years, a large amount of data on two types of injection – CO_2 and water – have been collected that greatly improve our understanding and management of the seismicity risk. About half of the CO_2 injection projects report seismic monitoring. None have had seismic events that were problematic for operations and the continuation of the project. In some cases, high quality measurements of low magnitude events and modeling has helped to understand the evolution of the pressure field related to the flood operations. In other cases, events have been small and sparse, and build confidence that seismicity is not a major risk in the project area.

High volume water injection both for hydraulic simulation via intentional inducing of fractures in the reservoir to improve production and for subsurface disposal of large volumes of produced brine has caused felt seismic events in some areas where hydraulic simulation was applied. Overall, we need better hypocentral depth detection (that we can get with dense networks and accurate earth models). Also, sometimes the fault zones are only on the shales and below it, so the layer on top of the shales is a barrier (both for seismicity migration and pore pressure transfer) to and from the shallow injection zones. However, as we spend more time working on this topic, we find that seismicity is on both zones (hydraulic stimulation and injection zones) following different causal mechanisms. Seismicity information (spatio temporal distribution, fault plane solutions, waveform cross correlation relative relocation) along with accurate fault information (from seismic) are the key parameters to provide accurate/reliable conclusions. The substantive learnings from injection management, government response and numerous studies are of high value for application to CCS. Learnings in terms of project siting, monitoring, injection management, regulation, and public acceptance have been in general effective, pragmatic and allowed a balance between proceeding with projects and management of risk to be attained.

From this experience we can make the following recommendations:

- Large scale injection planning should proceed. The summary of experience shows that induced seismic risk from injection is within the range of ordinary project uncertainties and can be reduced by available technologies during characterization, permitting, and operation.
- Investment in both historical data on seismicity and state of stress and data collection focused in the project area is needed for input into geomechanical models to assess risk. Based on analysis of existing data, many areas of highest risk can be identified during site selection. Further site specific data collection during characterization can substantially further decrease risk. Many locations can be demonstrated based on past experience and characterization to have low risk of seismicity.
- Collection of data during injection can further reduce risk. If a trend toward unacceptably high magnitude, frequency or likelihood is modeled based on initial responses, changes in injection strategy can be planned to reduce risk. Examples of such changes are shown in the Decatur projects, which moved the injection interval to a shallower zone to reduce the pressure communication with basement, and the Cogdell project, which reduced seismicity by changing the injection/withdrawal patterns.
- Because the pressure elevation extends over a large area, the possibility of detectible seismicity in the project area cannot be eliminated. Project developers are recommended to prepare for this contingency. Recommended plans include 1) modeling the range of possible responses to changes in state of stress 2) monitoring seismicity during injection and improving models, 3) preparing a risk mitigation plan should unexpected events occur, and 4) developing a transparent and trust building communication process with stakeholders, such that they are well-informed about the processes in place (risk mitigation plan) to manage seismicity.

Additional work is needed. We make this report at the mid-point of learnings from increased monitoring and CCS experience, continuation of the current trajectory of learning will substantively increase confidence in injection site selection and management.

We make the following recommendations for further research to advance and mature the prediction and management of seismicity.

- Further analysis and synthesis of all the data collection and analysis now underway will be needed.

- Increased information on issues such as velocity modeling to locate hypocenters, mechanics of event triggering, methods for more effective identification of risk factors during characterization
- Low cost high value monitoring tools and analysis will further reduce risk and increase public and investor confidence.

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Regulatory Appendix

The Underground Injection Control (UIC) program consists of six classes of injection wells. Each well class is based on the type and depth of the injection activity, and the potential for that injection activity to result in endangerment of underground sources of drinking water (USDW). (Source: United States Environmental Protection Agency-EPA)

Table 5 The Underground Injection Control (UIC) program six classes of injection wells

Class I	Class I wells are used to inject hazardous and non-hazardous wastes into deep, confined rock formations. Class I wells are typically drilled thousands of feet below the lowermost underground source of drinking water (USDW).
Class II	Class II wells are used only to inject fluids associated with oil and natural gas production. Class II fluids are primarily brines (salt water) that are brought to the surface while producing oil and gas.
Class III	Class III wells are used to inject fluids to dissolve and extract minerals. Production wells, which bring mining fluids to the surface, are not regulated under the UIC program.
Class IV	Class IV wells are shallow wells used to dispose hazardous or radioactive wastes into or above a geologic formation that contains an underground source of drinking water (USDW). In 1984, EPA banned the use of Class IV injection wells. These wells may only operate as part of an EPA- or state-authorized ground water clean-up action.
Class V	Class V wells are used to inject non-hazardous fluids underground. Most Class V wells are used to dispose of wastes into or above underground sources of drinking water. This disposal can pose a threat to ground water quality if not managed properly.
Class VI	Class VI wells are used to inject carbon dioxide (CO_2) into deep rock formations. This long-term underground storage is called geologic sequestration (GS). Geologic sequestration refers to technologies to reduce CO_2 emissions to the atmosphere and mitigate climate change.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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