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**Methods and techniques employed to monitor
induced seismicity from carbon capture and
storage**

[D. D. McNamara](#)

**GNS Science Report 2015/18
October 2016**

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ABSTRACT

This report discusses the topic of induced seismicity resulting from the operations of sub-surface CO₂ injection at Carbon Capture and Storage (CCS) sites. The potential for induced seismicity to occur in CCS projects is an important factor when considering the capability of a project site's storage reservoir to retain injected CO₂ for long periods of time. It is also important when assessing and addressing public concern over earthquake activity. This report discusses the measures carried out at global CCS sites to identify and monitor induced seismicity. This information is then distilled into a list of issues to be considered as part of the review process prior to establishing a CCS site in New Zealand.

KEYWORDS

Induced seismicity, CO₂ injection, carbon capture and storage

1.0 INTRODUCTION

1.1 CARBON CAPTURE AND STORAGE (CCS)

Carbon Capture and Storage (CCS) is the process of capturing carbon dioxide (CO₂) from industrial (e.g., steel and cement production) and energy-related sources (e.g. power plants, natural gas processing facilities), and injecting it as supercritical CO₂ into deep subsurface rock formations for long-term storage via deep wells. The aim of CCS is to reduce the release of large quantities of CO₂ into the atmosphere, providing a means of mitigating the contribution of greenhouse gas emissions to global warming (Haszeldine, 2009; Metz et al., 2005). CO₂ injection into deep rock formations has been operating for many years for purposes such as enhanced hydrocarbon recovery. Larger scale injection, specifically for storage, has been developing for more than twenty years and involves different technical issues and potentially larger volumes of CO₂ than have been attempted in the past.

CCS projects with the goal of commercial long-term storage of CO₂ (>1 Mt/year) began at Sleipner in 1996 and the first large-scale, commercial CO₂ injection project was in the Weyburn oilfield, Saskatchewan Province, Canada. CO₂ injection in Weyburn began initially for enhanced oil recovery and eventually developed into its own project with the target of storing over 30 Mt of CO₂ (Verdon et al., 2013). A handful of similar, large scale CCS projects and experimental test sites have since been initiated; In Salah in Algeria, Sleipner and Snøhvit gas fields in Norway, Otway Basin in Australia, Cranfield oil and gas field and Frio Field in the USA, Nagaoka in Japan, and Kretzin in Germany (Figure 1) (Michael et al., 2010). Targeted geological formations for storage usually comprise depleted hydrocarbon fields, saline formations, or coal seams.

A desktop assessment of CCS opportunities in New Zealand revealed there may be a storage capacity of ~15000 Mt of CO₂ onshore (King et al., 2009). Therefore, it is prudent to develop best practises and explore the development benefits and risks of New Zealand's CCS potential before the need for CCS arises. This includes understanding the links between CCS and induced seismicity (IS), and how to monitor seismicity should a CO₂ injection project proceed in New Zealand. This report summarises information on induced seismicity experienced in overseas CCS operations, and how it is monitored, as a basis for assessing potential future CO₂ injection IS in New Zealand.

1.2 CCS INDUCED SEISMICITY

The potential for induced seismicity to occur in CCS projects is an important factor when assessing the integrity of potential sites as CO₂ storage reservoirs, and addressing public concerns over earthquake generation by CO₂ injection (Rutqvist et al 2014; Vilarrasa et al., 2013; Myer et al., 2011; Wurdemann et al., 2010; White et al., 2003). Induced seismicity can be the instigation of seismic events of any magnitude as a result of production or injection activity in a number of industries, e.g., oil and gas production, geothermal energy production, CCS, and waste disposal. In CCS projects, induced seismicity is potentially a consequence of a) pressure from injected CO₂ surpassing i) the reservoir or seal rock strength to create a new fracture, or ii) surpassing a nearby structure's (fault or fracture) strength reactivating it (Cappa and Rutqvist, 2011), and b) fluid-rock chemical reactions which alter the reservoir and seal rock mechanical properties to the point where fracture generation can occur (Sminchak and Gupta, 2002).

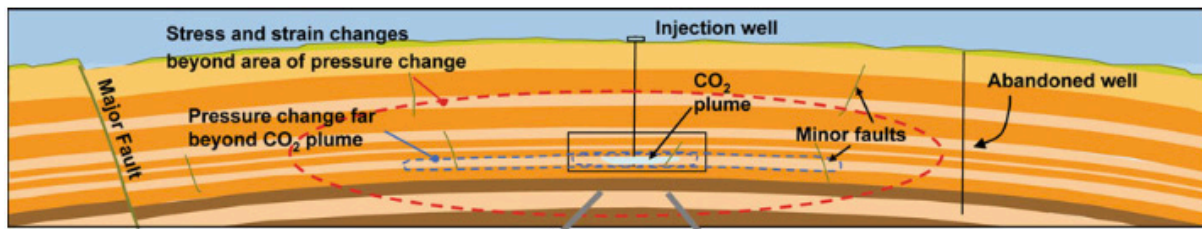
Nicol et al. (2011) carried out a global study of induced seismicity from sites dominated by water injection and hydrocarbon extraction to assess potential implications for IS linked to CO₂. They found that the rates and magnitudes of the induced seismic events increased with rising reservoir pressures, fluid volumes, and injection/extraction rates and stated this may also be true for CO₂ injection and storage projects. The record of induced seismicity from CCS is very small, due to the few sites in operation and a lack of local IS monitoring at these sites (IEAGHG, 2013; Verdon et al., 2013; Gerstenberger et al., 2012). Publically accessible information on CCS induced seismicity is also small, with the exception of the Weyburn and Cranfield projects. This makes it difficult to assess the direct effects of CO₂ injection on seismicity.



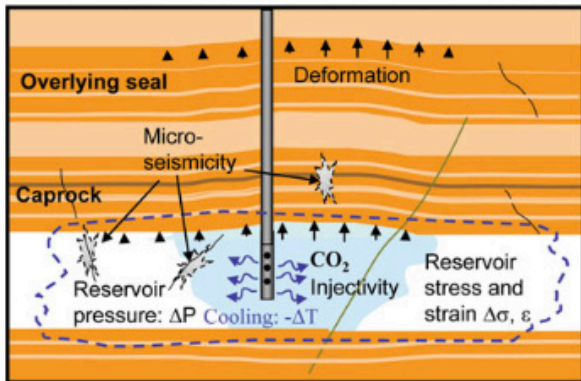
Figure 1 Location map of large scale CO₂ injection projects and experimental test sites.

The risk of induced seismicity at a CCS site is in part dependent on the geology, and physical and mechanical properties of a site's reservoir and cap rock, and the injection pressures and time over which injection occurs (Vilarrasa et al., 2013; Rutqvist, 2012) (Figure 2). A critical risk is that continual injection over time may create or reactivate fracture and fault networks in the sealing cap rock, permitting leakage (Verdon et al., 2013). A sensible policy would be for potential sites to undergo rigorous geological mapping and geomechanical modelling, combined with risk assessment before the injection of any fluids is performed.

a)



b) Injection-induced stress, strain and deformation



c) Unwanted mechanical changes

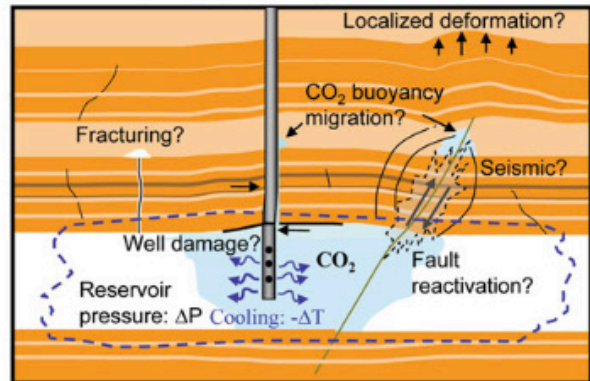


Figure 2 Geomechanical processes associated with CCS in deep sedimentary formations. A) Regions that can be affected by a CO₂ plume, reservoir pressure changes, and geomechanical changes in a layered and faulted geological system. B) Injection induced stress, strain, deformation and induced seismicity result from changes in reservoir pressure and temperature, C) The potential negative impacts of CCS induced changes in the reservoir. From Rutqvist (2012).

2.0 CCS IS MONITORING TECHNIQUES AND RESULTS

The following summarises the equipment and techniques utilised in various CCS projects used to monitor induced seismicity, and their various successes and problems. From nearly all studies of CO₂ injection-related induced seismicity, microseismic monitoring and data acquisition are deemed essential for any project. These also aid understanding and monitoring of reservoir deformation (Verdon et al., 2013).

2.1 WEYBURN, CANADA

At the Weyburn project, a passive seismicity array was used to detect seismicity during CO₂ injection that occurred between August 2003 and December 2007, and also during a period prior to CO₂ injection (Verdon et al., 2012; 2011; 2010b) (Figure 3, Figure 4). The passive network consisted of eight triaxial, 20 Hz geophones, deployed in a vertical monitor well ~50 m from the CO₂ injection well. Geophones were spaced at intervals of 25 m between depths of 1181 and 1356 m (~200 m above the targeted reservoir). The system was operated in “triggered” mode using a trigger window of 200 ms and required processed signal levels to exceed threshold on five out of the eight geophones for event triggering and data storage to be initiated (Verdon et al., 2010b).

This network measured ~200 earthquakes which were located to within ~±100 m and ranged in magnitude between -3 M to -1 M (Verdon, 2014; 2011). From this data, determination of actual seismic events from background ‘noise’, and accurately locating those seismic events that could be determined, was difficult. This was thought to be due to the configuration and small number of seismographs in the monitoring array. Additionally, the magnitudes of the suspected induced events were too small to be picked up by the Canadian regional network (Gerstenberger et al., 2012), providing no extra information to assist interpretation. The determination of the cause of observed seismicity was further hindered by incomplete monitoring of water injection operations during the sampling period.

Overall, results from Weyburn indicate low rates of microseismicity (events <2 M) (Gerstenberger et al., 2012; Verdon et al., 2010a). This has been attributed to either the geomechanical nature of the reservoir or the reservoir geometry which makes it unlikely to fracture (Verdon et al., 2008; Jimenez et al., 2004). Seismicity recorded pre-CO₂ injection was related to completion activities of the injection well, or other well operations such as well shut-ins, which resulted in local pressure recovery, or were related to a period of water injection.

The locations of some seismic events at Weyburn correlate with regions of CO₂ saturation, as determined from 4D seismic data. This supports the view that CO₂ injection may be the source of these seismic events. It was expected that induced seismicity at the Weyburn site would occur around the CO₂ injection well, before moving radially outward. However, the majority of detected seismicity that occurred post CO₂ injection, was located around the production wells, with a number of seismic events located above both the reservoir and cap rock. These seismic location patterns implied a connection between reservoir and overburden, and thus a potential CO₂ leak point within the system (Verdon et al., 2012; 2011; 2010a; 2010b). A better understanding of the spatial patterns of induced seismicity observed at the Weyburn site was established by combining shear wave splitting analyses and geomechanical modelling (Verdon et al., 2011). It was discovered that due to the unique geometry of the injection and production wells at this site, CO₂ injection increased effective shear stress around the production wells rather than around the CO₂ injection well, as was expected. This elevated shear stress around and above the production wells explained the predominance of induced seismicity at these locations.

CCS IS monitoring at the Weyburn oil field resulted in a recommendation for a combination of local, passive seismograph networks, comprising a number of subsurface instruments, in order to measure the expected level and magnitudes of CO₂ injection IS (Verdon et al., 2010b). A dense network of surface seismometers would be required to detect IS events due to the low magnitudes recorded. Even then it would be difficult to separate such events from surface noise and to determine the nature of their focal mechanisms. Many recorded events had frequencies close to the resonant frequency (20 Hz) of the geophones, which inhibited determining their locations (by up to 100 m in depth; Verdon et al., 2011). Extended vertical arrays, or multiwell arrays, would better constrain depth locations of induced seismic events, as well as improve the density of gathered data (Gerstenberger et al., 2012; Verdon et al., 2010b).

The benefits of installing a passive seismic monitoring array include its cost effectiveness, particularly over long periods of time, as the geophone arrays cost little to maintain (Verdon et al., 2010b). This is useful for a CCS site which may need to be monitored long after the CO₂ injection has finished and the field has been shut in. However, passive seismic monitoring can only image areas between where microseismic events are occurring and receivers are located (Verdon et al., 2010b), thus it is important to optimise the geometry of such a passive array of geophones to capture relevant seismic events. The use of additional downhole instruments deployed in multiple monitor wells at Weyburn has been suggested in order to improve the understanding of CCS IS there.

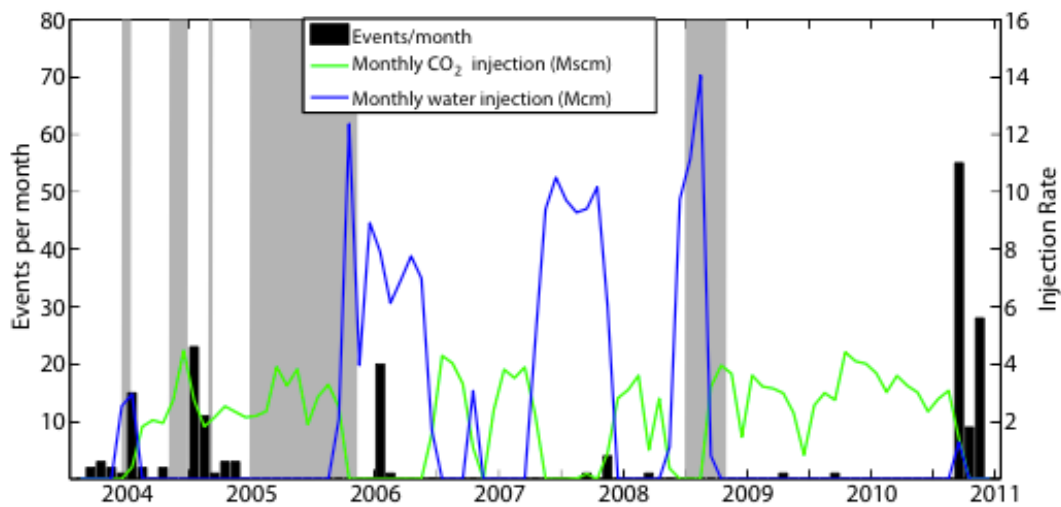


Figure 3 Rates of CO₂ and water injection and measured rates of microseismicity at the Weyburn site. Grey shaded areas indicate periods of time where the monitoring array was inoperative. From Verdon et al. (2013).

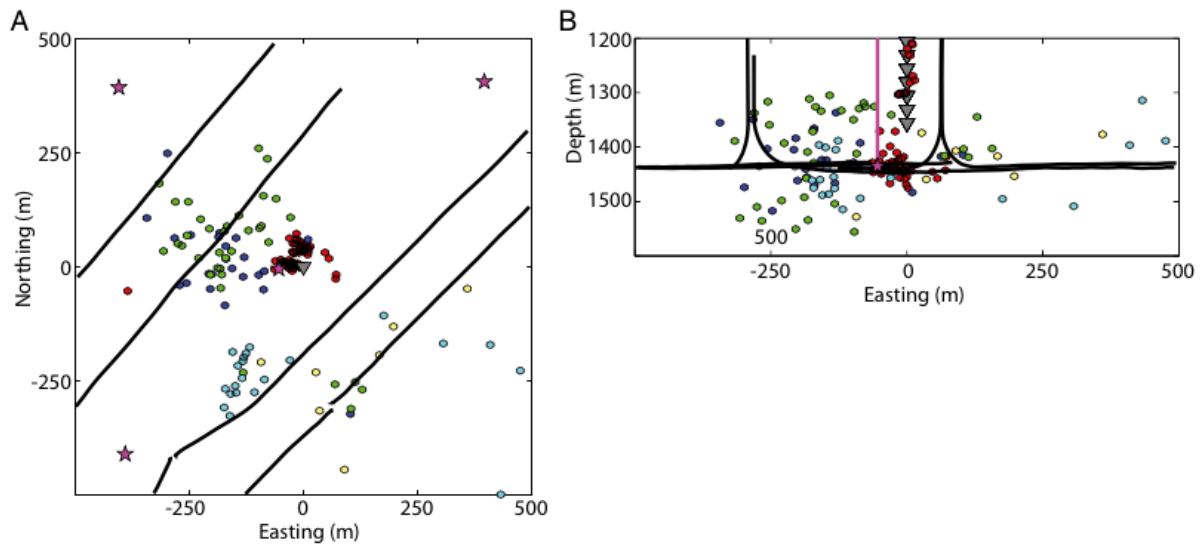


Figure 4 Locations of microseismic events recorded at the Weyburn site between 2003 and 2010 in map view (A) and projected onto an E-W cross-section (B). Events are coloured by occurrence time: before CO₂ injection (yellow), during initial injection stages (dark blue), during elevated injection (green), second monitoring phase (light blue) and after injection well shut-in (red). A) Injection wells (stars), monitor well (grey triangle), horizontal producing wells (black lines). B) Geophones (grey triangles), injection wells (purple lines), and production wells (black lines). Reservoir interval approximately coincides with the depth of the horizontal wells. From Verdon et al. (2013).

2.2 IN SALAH, ALGERIA

At In Salah the location of the injected CO₂ plume, and the integrity of the caprock have been monitored using 4D seismic reflection surveys, gravity, VSP, shallow aquifer wells, deep observation wells, InSAR, and via a passive seismic geophone array (Stork et al., 2013; Verdon et al., 2013; Mathieson et al., 2010; Vasco et al., 2010; Chadwick et al., 2009; Mathieson et al., 2009). The passive seismic geophone array was composed of six, three-component geophones placed ~500 m into a vertical test located ~1500 m above the KB-502 CO₂ injection point (Verdon et al., 2013; Mathieson et al., 2010). The seismic array was installed at In Salah several years after CO₂ injection began and thus did not capture any induced seismicity associated with the deformation that had already occurred in the field. Due to technical problems only one of the six geophones has provided usable data (Verdon et al., 2013; Daley et al., 2011). Locating the recorded seismic events (>1000) from triangulation from multiple geophones has therefore not been possible, though seismicity rates have been determined (Figure 5), providing further information on the geomechanical deformation induced by CO₂ injection at In Salah.

The In Salah geophone array has recorded >1000 seismic events (the largest magnitude recorded is 1.6 M), with a cluster of activity in mid-2010, most of which is attributed to CO₂ injection (Verdon et al., 2013; Stork et al., 2013). It has been shown that CO₂ injectivity at In Salah is pressure-dependent, implying that CO₂ flow is at least partially dependent on the opening and closing of fractures in the reservoir (Bissell et al., 2011). Surface deformation had been detected from InSAR methods which revealed doming of the ground by up to 25 mm over each of the three injection wells. This is attributed to the first five years of CO₂ injection (Vasco et al., 2010; Onuma and Ohkawa, 2009). This surface deformation is consistent with a ~10 MPa increase in reservoir pressure causing dilation of the reservoir. Geomechanical modelling of the site has suggested that reservoir deformation is occurring on pre-existing fractures rather than generating new fractures (Rutqvist et al., 2011).

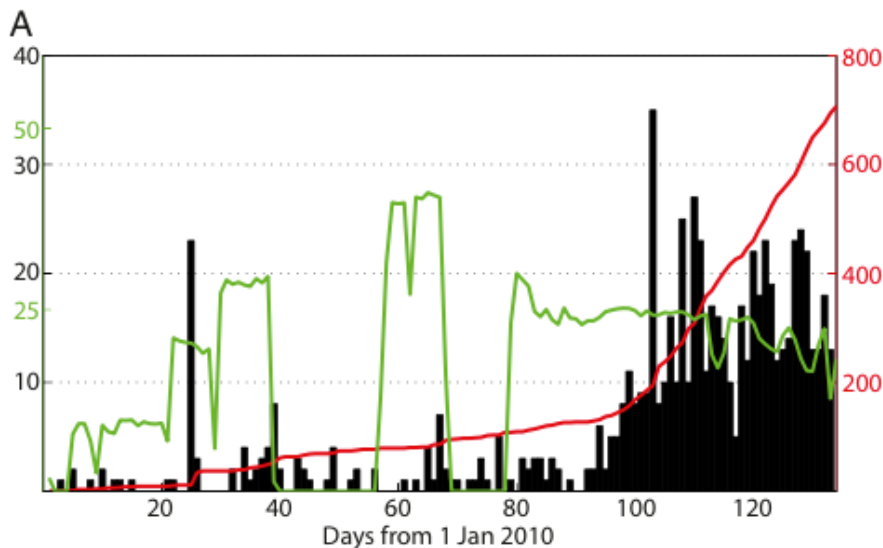


Figure 5 Microseismicity at In Salah. Rates of microseismicity (per day, black) and cumulative number of events (red) during the first four months of 2010, CO₂ injection rate (green). From Verdon et al. (2013).

2.3 OTWAY, AUSTRALIA

Monitoring the seismicity at the Otway site was begun approximately six months before CO₂ injection, though no data on recorded seismicity during this time is available. CO₂ injection was carried out in two phases (Gerstenberger et al., 2012). A two-channel seismometer, connected to a pair of triaxial geophones, was installed at 10 m and 40 m depths in the Naylor-1 well, above the reservoir (Gerstenberger et al., 2012). During the first stage of CO₂ injection 0-36 'seismic events'/day were recorded with estimated maximum magnitudes of 1 M. However, distinction between these events and ambient noise was unclear, and the limited geophone array at the time made locating the events difficult ($>\pm 100$ m).

A second downhole array of geophones and hydrophones were installed, in addition to the first pair, at reservoir depths in the Naylor-1 well, but ceased to operate after several months, providing limited data. The initial array was augmented three years after CO₂ injection had begun by the addition of four more geophones in two more wells (two downhole, triaxial geophones at 10 m and 40 m depths). The current array comprises these six geophones arranged in a triangular geometry around the CRC-2 CO₂ injection well. This system has measured >100, dominantly -1M to -2M, seismic events during the second phase of the project (Gerstenberger et al., 2012). Only one -1M event triggered all six geophones and was linked to CO₂/water injection. Overall, microseismic monitoring indicates low levels of seismicity with magnitudes of less than 0 and no clear correlation with injection pressure history (Myer and Daley, 2011). It has been suggested that the seismic magnitudes recorded may be associated with shear slip along fractures with radii of ≤ 1 m (Rutqvist, 2012).

2.4 KETZIN, GERMANY

The passive seismic array employed at Ketzin consists of 3-component-geophones at the surface, 4-component-recievers at 50 m depths, and a central, vertical array of 4-component-recievers at locations along a 120 m line (Figure 6) (Paap et al., 2013; Arts et al., 2013). Distinguishing background noise from actual seismic events at the Ketzin site makes it difficult to quantify any induced seismicity (Arts et al., 2013). Background seismicity in the area is very low and no seismic events have been reported as 'felt' at the site (Evans et al., 2012; Paap et al., 2013). A common issue with CCS seismicity monitoring is that the array designs are not

optimised for detecting events above background noise levels or for determining accurate locations (Arts et al., 2013; Gerstenberger et al., 2012).

Despite the lack of recorded seismicity, the Ketzin site reported that CO₂ injection rates of 50–500 t/day increased reservoir pressures to 1.7 MPa more than original values (Wurdemann et al., 2010). A 3D geomechanical study of the CO₂SINK experiment at Ketzin, Germany, was linked to a reservoir model and the stress path and rock deformation associated with CO₂ injection was simulated (Ouellet et al., 2011). This model was used to calculate stress paths and strain that might induce cap rock failure and the likely locations where this could happen. It was found that for current CO₂ injection volumes there was low risk of failure in the caprock and activation of faults in the field.

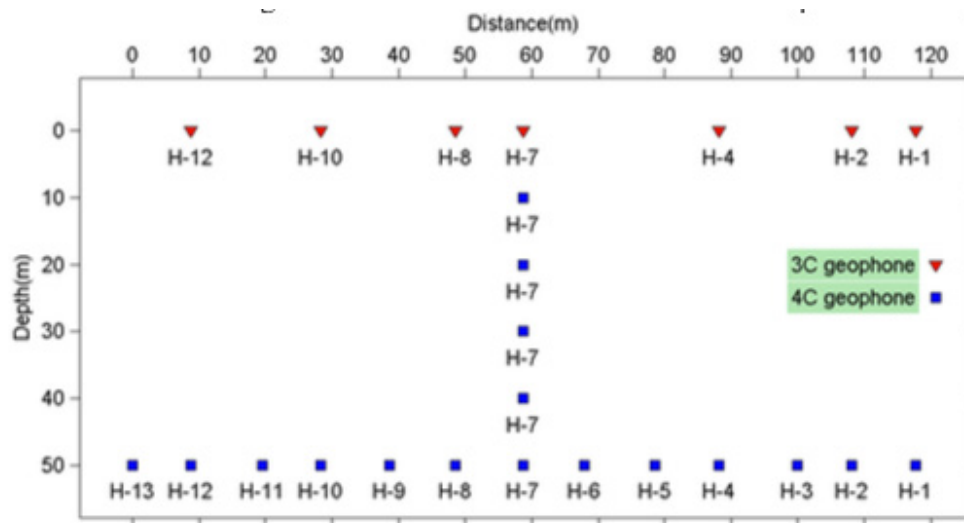


Figure 6 Layout of the individual geophones and hydrophones in 13 boreholes at the Ketzin Site. From Arts et al. (2013).

2.5 OTHER SITES

Seismicity monitoring at the Nagaoka CO₂ injection test site in Japan was carried out using one downhole, multi-channel, hydrophone array placed in an observation well in combination with one test site surface seismometer (Kikuta et al., 2005). Monitoring was carried out continuously to detect seismicity (Gerstenberger et al., 2012; Kikuta et al., 2005) though no significant relationship with CO₂ injection has been found by this method to date.

The Cranfield site at Mississippi, USA initially employed a surface seismic array during CO₂ injection but no seismicity was recorded (Hovorka et al., 2013). A near-surface seismic network was added later consisting of three 1 Hz, servo-type, velocity seismometers with a frequency range of 0.018 – 80 Hz, installed at depths of 90 m, deployed across a 3 km radius. This array has detected 15 earthquakes at the Cranfield site (Figure 7), though few are reported as induced seismic events (Takagishi et al., 2014; Hovorka et al., 2013; Gerstenberger et al., 2012).

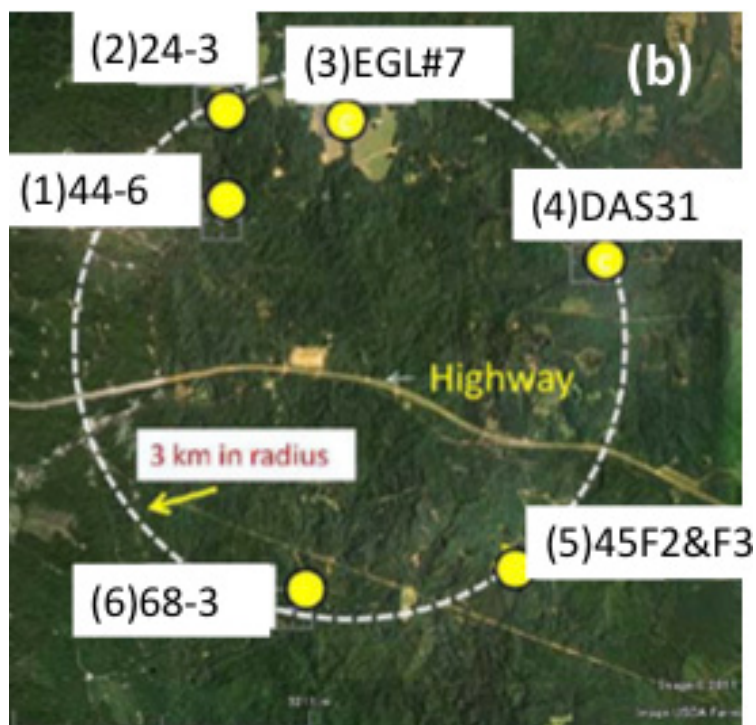
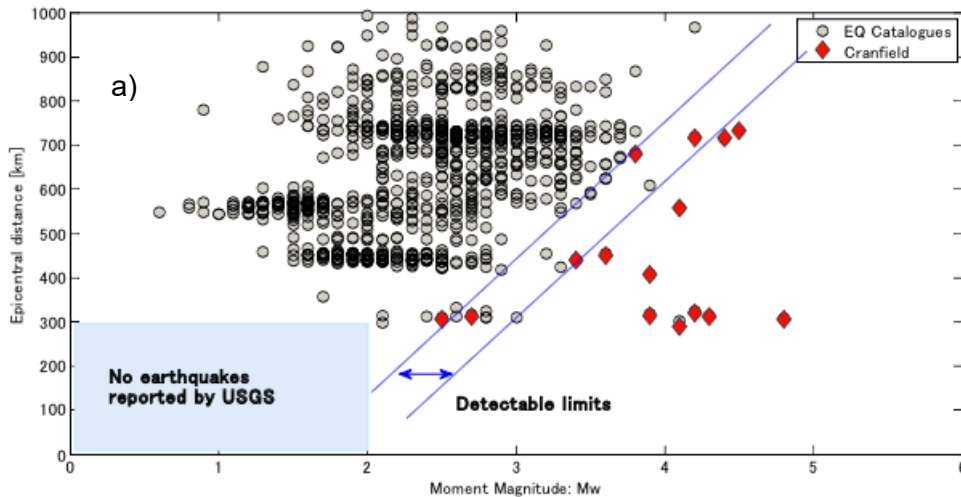


Figure 7 Cranfield CCS Site seismicity. A) Relation of earthquake magnitudes and epicentral distances from the Cranfield Site (grey symbols = natural earthquakes reported by USGS, red diamonds = earthquakes recorded at Cranfield Site, blue lines = Detectable limits of magnitudes and epicentral distances). B) Map of the seismic monitoring network at the Cranfield site. From Takagishi et al. (2014).

In the Sleipner field, downhole reservoir pressures increased by <0.5 MPa since injection of CO_2 commenced. A regional seismograph network measured earthquakes of 2–3 M within 50 km of the Sleipner Platform A in the time since CO_2 injection began in 1996 (Gerstenberger et al., 2012). This network has not recorded seismicity induced by the injection program, and no ‘felt’ induced seismicity has been reported (Verdon et al., 2013; Evans et al., 2012). The absence of a local microseismicity monitoring system means CO_2 injection induced seismic events cannot be ruled out.

3.0 DISCUSSION

Where it has been recorded, CCS IS is represented by small numbers of seismic events (<100/year) with low magnitudes (-2 M to 1 M). For those fields where induced seismicity is monitored (In Salah, Otway, and Weyburn) events recorded have had such low magnitudes that they were only detectable using geophones and are not 'felt' (Rutqvist, 2012).

A seismic event recorded during CCS site operation is, on its own, only partially useful in understanding whether it was induced or otherwise. Key to removing uncertainty and limitations of whether seismicity recorded is related to CO₂ injection are a) pre-injection monitoring to establish a baseline of seismicity at a potential CO₂ injection site, b) good reporting of intermittent injection and extraction volumes and operations across the field, and c) ensuring equipment can measure small magnitude seismic events (<2 M) (Verdon et al., 2013; Nicol et al., 2011).

When determining the risk of induced seismicity at a potential CCS site it is useful to have some knowledge of the existing seismicity of the area (both natural and that potentially induced by existing field operations) (Verdon et al., 2013; Nicol et al., 2011). As such, preliminary acquisition of seismic event data (rates, locations, and magnitudes) utilising appropriately designed detection networks, before CO₂ injection begins is required in order to better understand the effects of CO₂ injection on the reservoir. Without this, determining whether large scale seismicity is tectonic or induced is difficult.

However, care should be taken with the establishment of a baseline for seismicity of an area, as seismicity can be non-stationary, either temporally or spatially (Corral, 2004; Vere-Jones, 1983). For example, before the Darfield earthquake in 2011, the Canterbury Plains had been an area of low seismicity in New Zealand for as long as records have been kept (Kaiser et al., 2012). Use of a stationary seismic record may lead to inaccuracy when modelling seismic risk, and could lead to inaccurate assumptions on the cause of changes in the level of seismicity in an area.

Linking seismic events to injection and extraction of fluids may be done by looking at their spatial distribution within the reservoir and the injection site in the well, as well as temporal correlation to the duration of various well activities and potential, associated, lingering pressure effects. Existing CCS IS studies, such as those at Weyburn and In Salah, highlight the need to couple observations of induced seismicity, surface deformation, and field operations with a robust geomechanical model. Geomechanical models of the storage site are important for understanding the cause and locations of seismic events recorded during CO₂ injection and later storage. Therefore, knowledge of the rheology of the reservoir rock and caprock, and development of a good pre-injection geomechanical model of the reservoir are considered crucial (Rutqvist, 2012; Verdon et al., 2013; 2012; Zoback, 2010). This will allow forward modelling of the stress field response to various injection strategies and help identify the potential for induced seismicity.

The small amount of data from current CCS IS projects is argued to be, in part, due to the nature of the equipment being used to monitor IS, and the deployment of such equipment. In terms of equipment, most studies state that the seismic waves generated by micro-earthquakes (usually -3 M–0 M), which can compose the bulk of induced seismicity, can only be detected by geophones placed in boreholes near the reservoir or by a dense array of geophones at the surface (Verdon et al., 2013). In addition, the number and arrangement of seismometers limits the number and range of seismic events that can be recorded (Nicol et al., 2011).

Given the lack of available data on CCS IS, it seems prudent to learn from other induced seismicity studies such as water injection. Such a comparison would need to take into account the different properties of CO₂ and water. The lower density of supercritical CO₂ may result in lower pressure increases and lower seismicity rates than with injecting water. Despite this, a comparison of seismicity from the injection of both types of fluid shows similar event frequency and magnitudes. Nicol et al. (2011) studied seismic data from 75 fluid injection and extraction sites and applied the following criteria as to whether events were induced: a) located proximal to, or within, the fluid injection/extraction reservoir, b) the measured or calculated state of stress in the reservoir and seal exceeds the rock strength, c) events occur during or immediately after injection/extraction, d) there is a clear temporal and/or spatial disparity between previous natural seismicity and inferred induced events. It is suggested these criteria be used as a basis for determining the conditions for CCS IS.

3.1 CCS AND IS REGULATION

As an initial step, any proposed New Zealand CCS project should consider current regulations governing aspects including, but not limited to: drilling (both on- and off-shore); property, resource rights and permits; transportation of CO₂; injection of fluids into a reservoir; hydraulic fracturing; and induced seismic monitoring. Most of the existing laws and legal framework pertaining to CCS projects in New Zealand are summarised and commented on in Barton et al. (2013). That report analyses existing law and regulation as it applies to CCS (both on- and off-shore) and makes recommendations for a legal regime that will make CCS possible in New Zealand, subject to proper regulatory constraints, and facilitates the evaluation of CCS projects and their implementation. Existing laws, including the Resource Management Act 1991, the Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act 2012, and the Crown Minerals Act 1991 do not fully deliver the legal framework required for CCS and thus a new legislation to manage it has been recommended.

In the United States CCS is governed by a set of regulations, including CCS induced seismic activity (Environmental Protection Agency, 2010). In December 2010, the United States EPA published the 'Federal Requirements Under the Underground Injection Control Program for Carbon Dioxide Geologic Sequestration Wells Final Rule'. The U.S.A. defines wells that inject CO₂ for long term storage as Class VI wells. These are a defined and separate class of well from industrial and municipal waste disposal wells (Class I), oil and gas related injection wells (Class II), those that inject fluids to dissolve and extract minerals e.g. uranium, salt, copper (Class III), those that perform shallow injection of hazardous or radioactive wastes (Class IV), and those that carry out shallow injection of non-hazardous fluids (Class V). In reference to seismic activity related to establishing and operating a Class VI well, information on the seismic history of the area, including depths and seismic sources, must be provided and a determination that seismicity will not interfere with containment must be made.

In the United States a testing and monitoring plan needs to be submitted for approval prior to operations of any CCS project. Once a CCS well has been drilled and begins operating, testing and monitoring of the well is required. With regards to monitoring IS there are no specific requirements; rather, seismic monitoring is only suggested as a potential indirect method to track the extent of the CO₂ plume and the presence of elevated pressure.

Best practice approaches to CCS induced seismicity have been examined in the literature as have lessons learned from studies of other sources of induced seismicity (Myer and Daley, 2011; Nicol et al., 2011). Myer and Daley (2011) suggest a seven step best practices approach to assessing and monitoring CCS induced seismicity:

1. Review existing regulations and establish dialogue with regional authorities
2. Assess natural seismic hazard potential
3. Assess induced seismic potential
4. Educate stakeholders
5. Decide whether to establish a microseismic monitoring network
6. Interact with stakeholders
7. Implement procedures for response to seismic events

4.0 CONSIDERATIONS FOR INVESTIGATING AND DESIGNING CCS INDUCED SEISMICITY MONITORING PROJECTS IN NEW ZEALAND

Based upon existing studies and techniques applied to monitoring CCS IS across the globe, the following considerations have been compiled. The aim is to guide the design of an IS monitoring program should a CCS project be established in New Zealand. They are divided into two parts: 1) recommendations surrounding investigations and modelling of a proposed CCS site, and 2) recommendations on how to monitor induced seismicity during operation of a CCS site.

1. Site investigation:

- Geological analysis of the potential reservoir and seal rocks including strength testing, structural character, CO₂-rock interactions, geophysical properties, and permeability and porosity should be compiled from any and all data sources (wireline logging, drill-core, surface outcrop, etc.).
- Geomechanical models of CCS reservoirs are invaluable tools in understanding induced seismicity. As such, a robust geomechanical model of any proposed CO₂ injection site should be attempted, based on the following data:
 - Stress directions and magnitudes (determined from density and sonic wireline logging, borehole imaging, earthquake focal mechanisms, shear-wave splitting analyses, leak-off and mini-frac well tests).
 - Pore pressure (determined from drill-stem tests, repeat formations tests, modular dynamic tests, and well pressure monitoring).
 - Strength properties of reservoir and cap rocks (determined from unconfined and triaxial laboratory strength testing, rock strength determination from wireline logs).
 - Fault and fracture orientations (compiled from fault mapping, borehole imaging, 3D geological modelling).
- Utilising both the geomechanical model and geological data of a CCS site, fault and fracture slip tendency modelling should be carried out as part of a risk assessment under various CO₂ injection scenarios.

2. Induced seismicity monitoring:

- Whether the CCS reservoir is located on-land or offshore will determine the types of induced seismicity monitoring techniques that can be employed.
- The type of ground surface (e.g. vegetation, land use) above a CO₂ reservoir site will determine which geodetic techniques can be utilised to analyse surface deformation related to injection, and the extent that microseismic detection techniques will be subject to sources of noise from infrastructure and surface activity.
- The optimal timeline to start an induced seismicity monitoring program is well before CO₂ injection begins at the proposed site. This will assist in establishing a background level of seismicity (both natural and from existing land-use/industry). However, the non-stationary nature of seismicity (temporally and spatially), should be considered as part of any assessment of background seismicity levels.

- The geometry of the array will dictate the success of any seismic monitoring before, during, and after the CO₂ injection phase. The number of geophones and their arrangement will determine how well seismic events can be distinguished from background noise (e.g. noises in pipe work and electrical pulses), and will govern the accuracy of locating recorded seismic events (<±50 m). The arrays that have been installed in current projects have reported effective ranges of 500–1000 m and thus may not fully cover the CO₂ reservoir injection volume of those sites (Verdon et al., 2013). In addition, it has been suggested that utilising a limited number of sub-surface geophones (<10) is partly responsible for the low recorded number of CCS IS most sites (Gerstenberger et al., 2012).
- The type of geophones utilised in a CCS IS monitoring array, particularly their frequency range, must be considered. The frequency range of small magnitude seismic events (low range frequencies) may be difficult to distinguish from that of ground noise and sensor self-noise, particularly by broad-band sensor geophones (Haskov and Alguacil, 2004). This problem is only exacerbated when injecting CO₂ into saline aquifers and permeable sand formations where injection often produces low amplitude seismic events which can be close to the noise floor of some geophones (Gerstenberger et al., 2012). Selecting geophones with frequency ranges that best enable seismicity to be distinguished from noise is essential in monitoring typically low magnitude CCS IS events (as low as -3 M).
- The depth a microseismic array is placed will affect the minimum detectable event magnitude (Villarresa et al., 2013). The ideal location to detect seismicity with magnitudes as low as -3M is at similar depths to the reservoir-cap rock system.
- The geothermal industry in New Zealand has experience with monitoring shallow crust (<3 km), induced seismicity that may provide valuable advice on appropriate seismic monitoring arrays and configurations (Sherburn et al., 2015).
- Monitoring bottom-hole pressures in CO₂ injection, and associated monitoring, wells penetrating the reservoir will allow operators to manage injection operations, and reservoir pressures, to ensure fracture pressure is never reached. This will reduce the likelihood of inducing fractures and associated seismicity.

5.0 CONCLUSIONS

Induced seismicity resulting from sub-surface injection of CO₂ has been identified and monitored in a variety of ways in the small number of existing CCS operations around the globe. These methodologies and their success and failure are summarised in this report. Suggestions for uptake in New Zealand, should a CCS project be initiated are proposed here based on reported experiences from existing sites.

Proposed measurements for monitoring and managing CCS induced seismicity fall under two broad categories:

- Site investigation:
 - robust geological mapping and modelling
 - geomechanical modelling
 - forward modelling of the stress effects of various CO₂ injection scenarios on geological structures to identify potential slip and dilation tendency.
- Induced seismicity monitoring incorporating:
 - carefully chosen equipment that:
 - can detect the low level and magnitudes typical of CCS IS.
 - is optimally arranged to locate any CCS IS events.
 - a firm understanding of the regional and local tectonics and seismicity that will allow:
 - establishment of natural seismic history prior to injection.
 - improved data sampling ability to distinguish IS from natural seismicity levels.

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