Stress Evolution During CO2 Storage- A Case for Long Term Monitoring

Mohammed Braim[1]*, Sheri Bowman[1], Breanne Waggott[1] discuss the results and lessons learned from a long-term seismicity monitoring for the CCUS Quest project near Edmonton, Alberta, Canada.

Introduction

Carbon Capture, Utilization and Storage (CCUS) is expected to play an important role in achieving net zero greenhouse gas emissions by 2050 (IEA, 2021). There are, however, risks associated with the long-term storage of captured CO_2 that are influenced by stress changes due to injecting large volumes of fluids, such as CO_2, into the subsurface.

Two such risks are i) breaching the containment of the geological seal and ii) generating seismic events of sufficient magnitude to be of concern to the public (i.e. induced seismicity). These risks can be mitigated through a process of careful site selection that considers the subsurface state of stress, the presence of pre-existing faults and fractures, the storage quality and capacity of the reservoir, and the quality of the geological seal. In addition, operational limitations on injection pressures, rates, and volumes provide a means of influencing the stresses induced by subsurface fluid injection. Remaining concerns about both CO_2 containment (Zoback, 2012) (Ringrose, 2013) and the potential for induced seismicity resulting from large-scale fluid injection (Zoback, 2012) (Goertz-Allmann, 2017) highlight the importance of verifying that CO_2 injection and storage projects operate safely. An important part of all CCUS operations is the Measurement, Monitoring Verification (MMV) plan, which includes methods to demonstrate containment (caprock and well integrity). Based on ESG's experience, one of the key elements to CCUS MMV plans is microseismic monitoring, which can be used to monitor containment risks within the area of interest (Figure 1).

Monitoring the seismicity generated due to CO_2 injection helps operators understand many complex problems such as geological features that are being activated, the effects of stress changes, and the trend in seismic activity. With each event providing the time, location, and attributes of the fault slip that occurs within the area of interest, operators can better understand the dynamic changes in the reservoir associated with CO_2 injection and use this information to inform any interventions to be taken. In this paper, we discuss a case study of a Carbon Capture and Storage (CCS) operation at Quest which illustrates the value of using microseismic to monitor CCUS operations that involve the injection of CO2 into the subsurface.

Case Study

The case study of this paper is Shell's Quest Carbon Capture and Storage (CCS) Facility located near Fort Saskatchewan, Alberta, which commenced CO2 injection in August 2015. CO2 is injected into a deep saline aquifer, the Basal Cambrian Sandstone (BCS), at a depth of about two kilometers below ground.

As part of this project, ESG installed a downhole array consisting of eight triaxial geophones (15 Hz) (Figure 2) in an observation well in 2014, which has been used to monitor the microseismic activity associated with the storage of CO2 (Harvey, 2021). To maximize coverage of the area, the array is installed in the middle of the area of interest, which is central to the three injector wells (Figure 3).

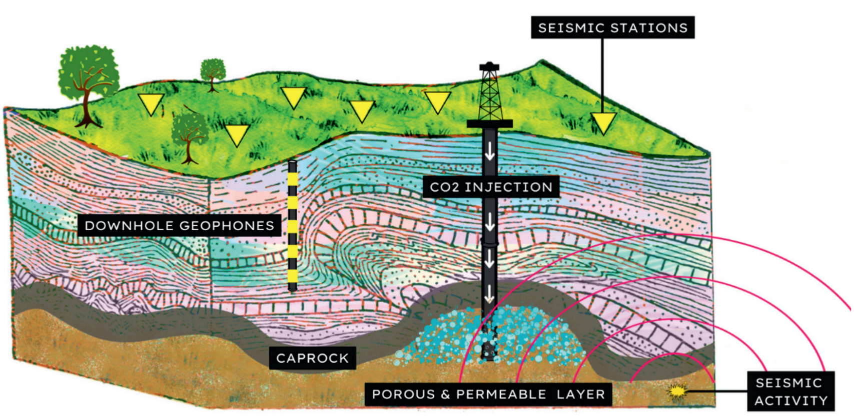

Figure 1 A generic representation of downhole and surface seismicity monitoring for a possible CCUS operation. It is not representative of the CCS operation at Quest.

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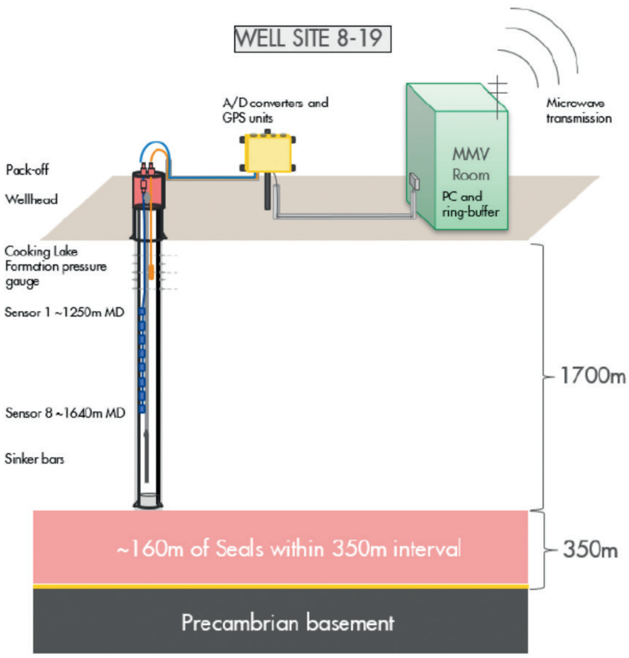

Figure 2 Schematic of the Quest downhole microseismic array and supporting components.

The Quest area is considered an extremely quiet tectonic location. This, combined with a geomechanical assessment of the storage complex and seal as well as a conservative injection pressure program, have resulted in an evaluation that the risk of loss of containment are low (Quest MMV Plan, 2020).

Results and observations

Over the seven years of monitoring microseismic activity associated with CO_2 injection at the Quest facility, a moderate number (more than 500 events) of microseismic events have been detected, of which analyses have been conducted to understand better the nature and distribution of seismicity (Figure 3). The results presented are from 2015 to 2021.

The moment magnitude of the detectable microseismic events ranged from -1.9 to +1 M_w with an average of -0.8 M_w (Figure 4). Many clusters of events have been identified, located both close and far from the injector wells. In the initial years of monitoring, it was unclear if the far-field activity observed was related to CO_2 injection operations. This activity may be related to the change of stress due to the pore pressure change over time or natural activation within the basement.

The spatial-temporal distribution of these events helps us to understand potential pressure/stress changes around the reservoir, providing insight into the behavior of the injected CO_2.

As can be seen in Figure 5, the downhole array provides the ability to reliably detect $M_w \geq -0.8$ for distances up to 10km radius from the monitor well.

The largest seismic event recorded within the 10km area of review has a moment magnitude $M_w<1$. The distribution of magnitudes suggests that supplementing the downhole 15 Hz geophone array with a lower-frequency sensor (e.g. 4.5 Hz geophones and/or broadband seismometers) would add value by improving moment magnitude estimates for Mw>0 events (Figure 7). The addition of a surface network would likely contribute positively to the determination of other source parameter (e.g. focal mechanisms), as well as reduce the azimuthal event location error resulting from the current downhole array geometry (Figure 3).

Figure 6 shows the seismicity distribution over time, which highlights that no seismic activity was detected in the first 10 months after the commencement of the CO_2 injection. The seismicity rate and the average magnitude increase significantly after the first year of monitoring and then start to stabilize. The average magnitude seems more consistent after this initial increase. The detection of several $0<M_w<1$ microseismic events demonstrates the potential for $M_w>1$ induced seismicity (Figure 8). In general, the rate of seismicity is consistent over time, punctuated by occasional periods of increased seismicity rate (eg: January 2019 - Figure 8). However, the seismic deformation (Figure 8),

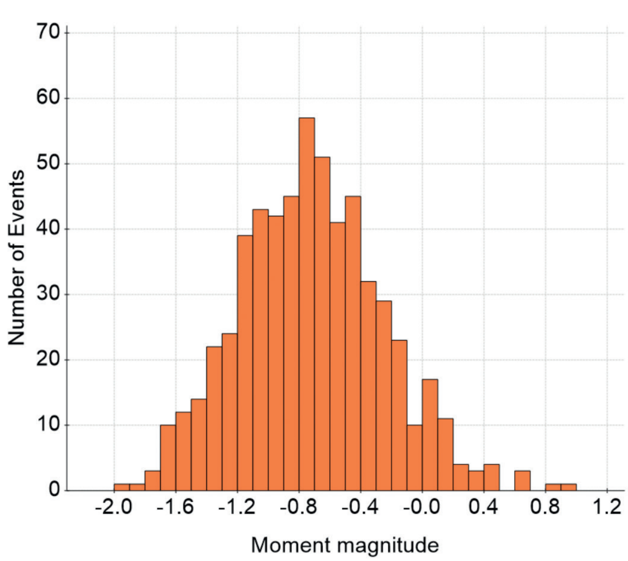

Figure 3 Observed seismicity over seven years. The events are colored by Moment Magnitude. The circles indicate the distance from the central of each injection well (10 km). the azimuth error for distant seismic events (circled by black) is much higher than the closest events.

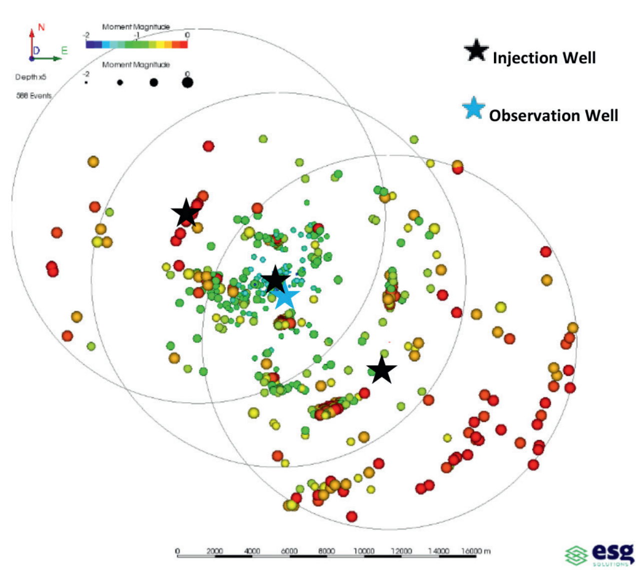

Figure 4 Observed seismicity over seven years. The events are coloured by Moment Magnitude. The circles indicate the distance from the central of each injection well (10 km).

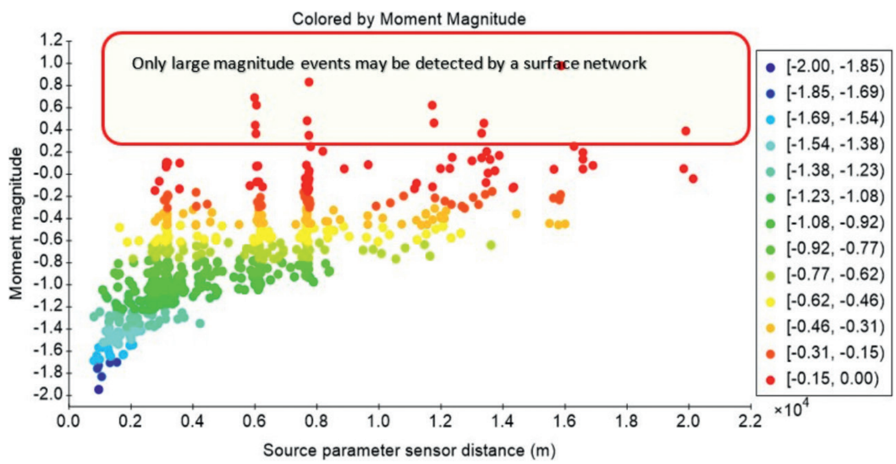

Figure 5 Magnitude distance plot.

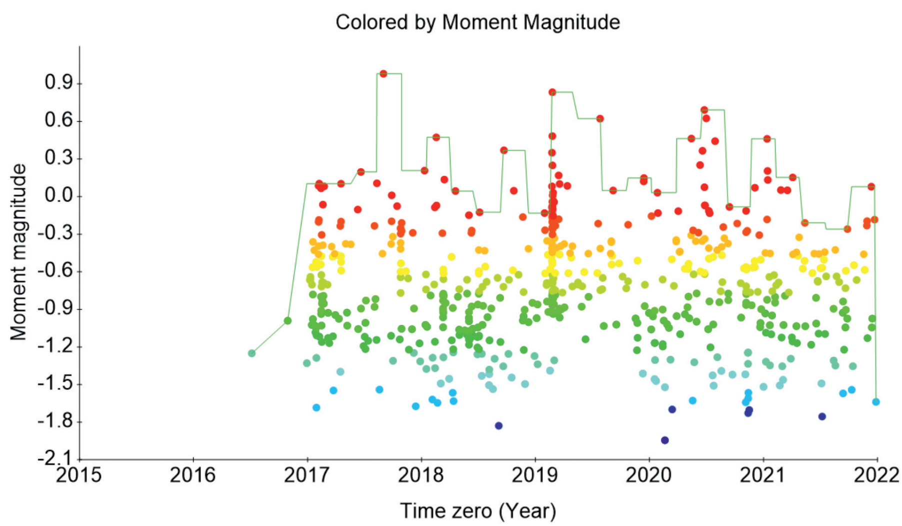

Figure 6 Seismicity distribution over time.

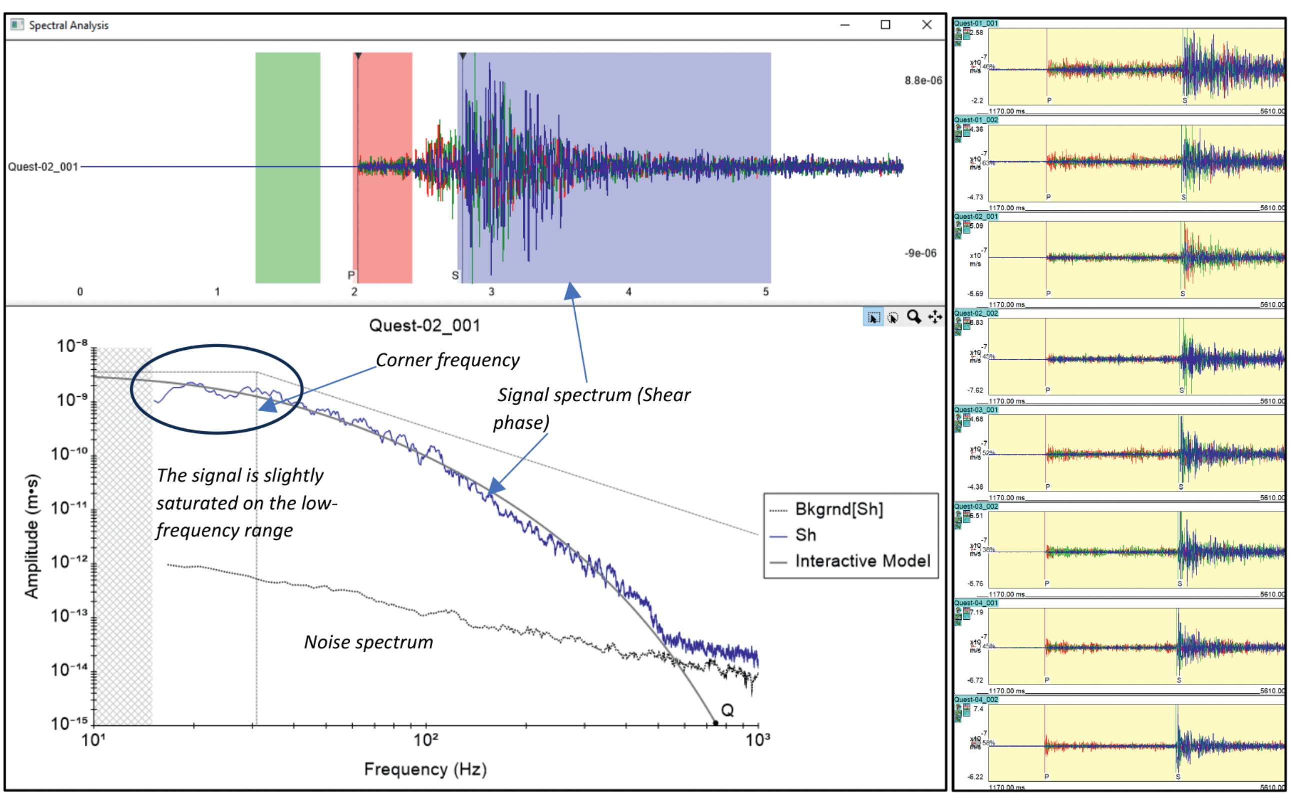

Figure 7 An example of saturated spectrum of a large magnitude event due the lack of the lower frequency geophone distribution.

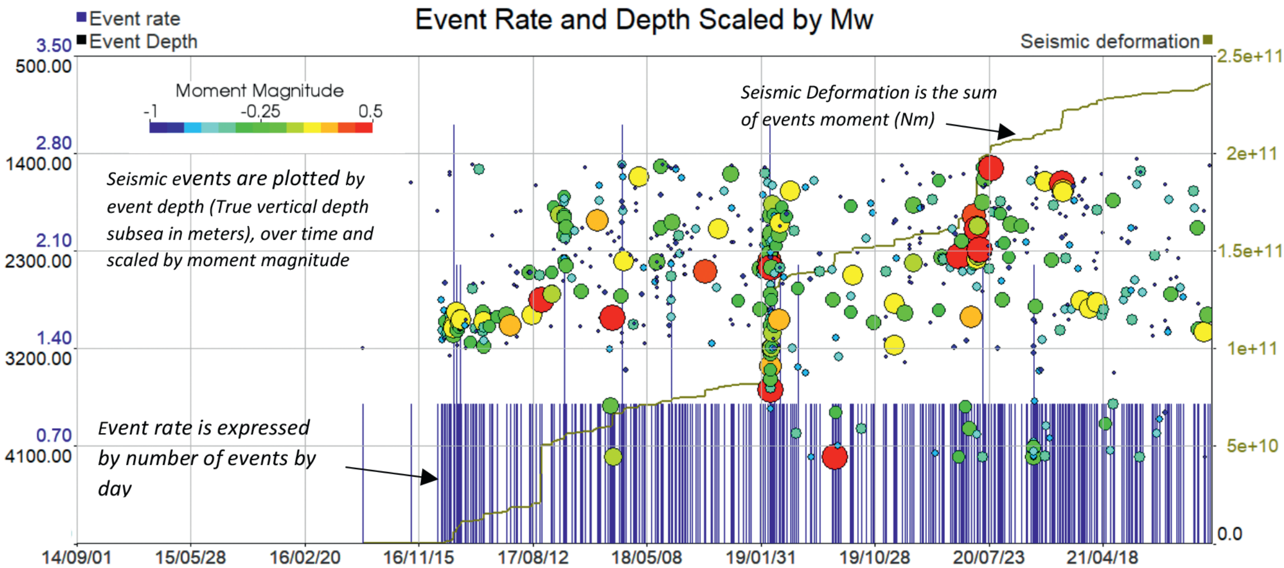

Figure 8 Seismicity distribution over time scaled by moment magnitude along the seismic deformation.

calculated from the cumulative seismic moment, shows a variable slope that is impacted by the rate and magnitudes of seismic events. The variability of seismic deformation over time indicates a dynamic response of the reservoir during the CO_2 injection. The sudden increase observed at the beginning of 2019 likely identifies an area of seismically activated features related to the ongoing CO_2 injection and associated pressure/stress changes of the reservoir that may be impacting the stress state of the basement.

The Importance of long-term microseismic monitoring

There was no microseismic activity around the injector wells in the first 10 months of CO_2 injection. After this initial period, microseismic activity was detected in the basement within the area of interest. In general, the seismicity rate seems consistent over time after the of first year but with periods of punctuated, increases in seismicity as shown on Figure 8. Without continuous long-term microseismic monitoring, such periods of clustered seismic activity can be missed.

To date, there has been no indication of a containment breach of the seal. The observed basement seismicity extending several kilometers away from the injector wells is interpreted to be the result of stress changes along features of weakness influenced by increasing pore pressures in the Basal Cambrian Sands. Such far-reaching effects are unsurprising as stress effects due to pore pressure and poro-elastic changes are expected to extend far beyond the extent of the injector wells and CO_2 plume (Zhang, 2013) (Segall, 2015).

As can be seen from the data presented, long-term seismicity monitoring provides valuable information to operators on containment and understanding the dynamic impacts from CCUS operations associated with stress changes. However, there are some limitations to using only one downhole microseismic array for long-term monitoring. The following points highlight good monitoring practices and complementary solutions taken from the learnings of this case study.

- Despite the benefit of the excellent detection capabilities provided by the downhole array, the location accuracy is impacted by the azimuth error and the aperture of the downhole array for distant microseismic events. To reduce the uncertainty of the event locations and the source parameters, a mixed array like ESG's HybridTM (surface seismicity monitoring stations and a downhole geophone array) solution is highly recommended.
- The observed seismicity is interpreted to be due to pressure/stress changes resulting from CO_2 injection into the BCS. Integrating other technologies may help to understand and correlate the seismicity with the extent of the plume of CO_2. ESG's Electromagnetic Imaging is a valuable tool which can image fluid/gas movement and can visualize CO_2 plume evolution. It images the increase in electrical resistivity caused by replacing existing fluid with highly resistive CO_2.
- Strain measurements are also a key factor in understanding the reservoir dynamic change associated with CCUS, which can be acquired from Fiber Optic DAS.

Conclusion

The results observed at Quest and the associated conclusions demonstrate the importance of long-term seismicity monitoring associated with CCUS operations. The below points highlight some conclusions observed from microseismic monitoring at Shell's Quest CCS project.

- Seismicity is contained within the basement, with no large magnitude events detected so far (M_w<1), showing no indication of compromising the storage seal.
- Long-term seismicity monitoring is a key technology to understand the response of the reservoir and for long-term risk mitigation associated with CCUS operations and maintaining license to operate.
- Using ESG's HybridTM solution (surface seismicity monitoring stations and a downhole geophone array) is highly recommended to improve the magnitude of completeness and reduce event position uncertainty. It will provide enhanced detection and accuracy within a large area.

- Integrating fiber and/or ESG's electromagnetic imaging will help with visualizing the extent of the perturbation caused by the CO_2 plume and measuring the strain variation over time, which can improve the interpretation of the observed seismicity.
- Establishing baseline seismicity before injection will help to distinguish between natural and induced seismicity.

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