

The Value of Hybrid Seismicity Monitoring for CCUS Operations

Mohammed Braim¹, Zahra Esmaeilzadeh¹, Breanne Waggott¹

¹ESG Solutions

Summary

Effective monitoring strategies are essential for demonstrating containment and conformance in carbon capture, utilization, and storage (CCUS) operations to meet regulatory requirements. A comprehensive approach necessitates a toolbox of monitoring solutions, among which passive seismic monitoring plays a critical role in assessing containment and stress changes associated with CO₂ injection.

This study evaluates the benefits of a hybrid seismic monitoring approach for CCUS applications. A hybrid system integrates surface-based instruments (seismometers and accelerometers) with downhole monitoring components, including fiber optic arrays, 15 Hz geophone arrays, and low-frequency geophones. The combined approach enhances the detection of microseismic events (-M) to larger-scale seismicity (M+), improves depth accuracy, and increases sensitivity to microseismic activity. Additionally, downhole geophone arrays, depending on their configuration, enable real-time monitoring of caprock and casing integrity. By capturing the full spectrum of seismicity, hybrid monitoring systems provide critical insights for containment assurance and risk mitigation.

This paper presents real-world data from CCUS projects and other subsurface injection operations to illustrate the advantages of hybrid seismic monitoring. The findings highlight the effectiveness of hybrid systems in improving the resolution and reliability of seismic data, thereby supporting the safe and efficient deployment of CCUS technologies.

Introduction

Injection-induced pressure perturbations within subsurface reservoirs can activate pre-existing geological discontinuities, leading to microseismic (-M3+) to earthquake-scale (M0+) seismicity. These seismic events predominantly localize along structurally weak zones, such as minor and major fault systems.

The spatial distribution of seismic events is highly site-specific and depends on the local stress regime, reservoir properties, and pre-existing structural features. Injection into reservoirs with high porosity and high permeability for example, can lead in seismicity at considerable distances from the injection zone, where pressure migration through permeable pathways affects critically stressed faults or mechanically weak formations. As illustrated in Figure 1, pressure diffusion can propagate beyond the immediate CO₂ plume boundary, potentially triggering seismic activity at considerable distances (Nicol, 2016).

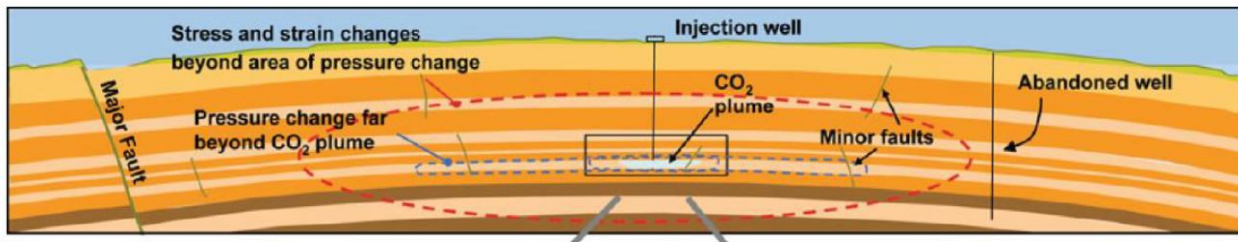


Figure 1: Influence zones of CO₂ plume migration, pore-pressure diffusion, and stress perturbation in a heterogeneous, multi-layered system with minor and major fault networks. Figure is taken from Nicol et al. (2016).

Earthquake-scale seismicity is typically recorded using surface arrays, which consist of seismometers, accelerometers, and low-frequency geophones. These instruments are optimized for detecting larger magnitude events (M0+), capturing ground motion over a broad area, and providing regional seismic data necessary for assessing seismic hazard and structural integrity. However, due to their limited sensitivity to lower-magnitude events and potential signal attenuation with depth, surface arrays alone may not provide sufficient resolution for monitoring smaller-scale seismic activity associated with subsurface fluid injection.

Microseismic activity, which typically consists of lower-magnitude events (-M3+ to M0), is more accurately detected and located using downhole geophone arrays. These arrays are deployed within boreholes at depths closer to the reservoir and typically consist of multiple 15 Hz and/or lower-frequency geophones. Their proximity to the source enhances signal fidelity, reduces attenuation, and significantly improves event location accuracy.

Additionally, permanently deployed fiber optic distributed acoustic sensing (DAS) systems can supplement both surface and downhole monitoring arrays. DAS utilizes fiber optic cables to detect seismic wave propagation along their entire length, providing a dense spatial distribution of sensors in contrast to discrete geophone placements.

By integrating surface, downhole, and fiber optic DAS monitoring components, a hybrid seismic monitoring system can offer a more comprehensive understanding of induced seismicity, enhancing the ability to detect, locate, and characterize seismic events associated with CO₂ injection and other subsurface operations.

Method

Hybrid monitoring for CCUS operations arms operators with powerful information for understanding the subsurface effects from injection. Table 1 presents a list of monitoring equipment configurations and the associated capabilities.

Table 1: Seismicity Monitoring Scenarios and Capabilities.

Solution	Magnitude of Completeness (Mc) *	Location Error	Real-Time Event Alerting	Ground Motion Measurement ⁴	Casing Integrity	Caprock Integrity	When
Private Surface Array ¹	~0 to 1 ML	X, Y- Low Z- High	Yes	Velocity	No	Limited to large-magnitude events	To provide enhanced location and magnitude accuracy and event detection, when compared to a public array.
Downhole Geophone Array Only ²	~-3+ Mw (>0 Mw underestimated source parameters)	Within 0-5 km from the array: X, Y and Z- low Within 5-20 km from the array: X and Y – high, Z very high	Yes	Velocity	Yes	Yes	A downhole array shows microseismic scale data, which can be used to better understand baseline seismicity and trends as stress builds in the reservoir.
Private Surface Array ¹ + Fiber (DAS MS)	~-0.5 to 1 ML (DAS supplements events >0 ML)	X, Y- Low Z- Low	Yes	Velocity	Yes Strain-around fiber	Yes Strain-around fiber	Combining the IS array with Fiber slightly increases event detection and improves depth accuracy of events above 0.
Private Surface Array ¹ + Shallow Downhole Geophone Array + Optional Fiber (DAS MS) ³	~-1.0 Mw (-1.5 ML)	X, Y- Low Z- Low	Yes	Velocity	Yes Strain-around fiber	Yes Strain-around fiber	If depth accuracy of events above -1 is important. To increase event detection and therefore better understand regional trends associated with injection. If noisy sites and sites with limited surface footprint.
Private Surface Array ¹ + Deep Downhole Geophone Array + Optional Fiber (DAS MS) ²	~-3 Mw (-1.0 ML Hybrid)	X, Y- Low Z- Very Low	Yes	Velocity	Yes	Yes Strain-around fiber	If depth accuracy of events above -3 is important. To maximize event detection, providing the greatest understanding of subsurface impacts from injection. If using for caprock or casing integrity or in-zone or fault monitoring.

This table is generalized based on a standard array of 5-10 stations.
 *Actual values vary based on project specifics. Mc varies based on array geometry, ground condition, surface noise, array depth. ML values vary depending on array geometry, ML formula, and associated parameters used.
¹ Private arrays can include public stations when available. Typical sensors used are seismometers.
² For this table, it is assumed the downhole array will use 15 Hz geophones. Low frequency geophone and or accelerometers can be included.
³ Fiber (DAS, DTS) can be added to supplement downhole coverage.
⁴ Ground motion in acceleration can be provided with an accelerometer, which can be placed on surface, shallow downhole, or as part of a downhole array deployment.

Well-constrained ML (local magnitude) relations for earthquakes have been developed. Yenier (2017) used a comprehensive ground-motion dataset from local and regional networks in the Western Canada Sedimentary Basin (WCSB). He derived attenuation model which corrects the ML overestimation especially at close distances. Mahani and Kao (2019) also presented the standard calculation of ML in the Western Canada Sedimentary Basin (WCSB) using an updated model based on recent ground-motion data. Their model is applicable for the vertical recorded Wood-Anderson amplitude.

In contrast, the moment magnitude (Mw) scale is a measure of earthquake energy, which quantifies the total energy released during fault rupture (Kanamori, 1977; Hanks and Kanamori, 1979). The moment magnitude is calculated based on seismic moment which is the scalar representation of earthquake size (Silver and Jordan, 1982).

In applications where only Mw is available, such as in downhole seismic monitoring, established empirical relationships between these two magnitude scales can be used to estimate ML. Such correlations are particularly useful for monitoring induced seismicity and assessing ground motion

impacts in regions where direct ML calculations are not feasible. However, these relationships are highly site dependent. Additionally, multiple studies indicate that for small earthquakes, moment magnitude tends to be systematically larger than local magnitude, with the discrepancy increasing as event size decreases (Yenier, 2017; Edwards et al., 2010; Bethmann et al., 2011; Ross et al., 2016).

Case Studies and Observations

Downhole Component- Geophone Array vs. Fiber Optic DAS

Two options for the downhole component of a hybrid seismic monitoring system include a geophone array and Fiber Optic Distributed Acoustic Sensing (DAS).

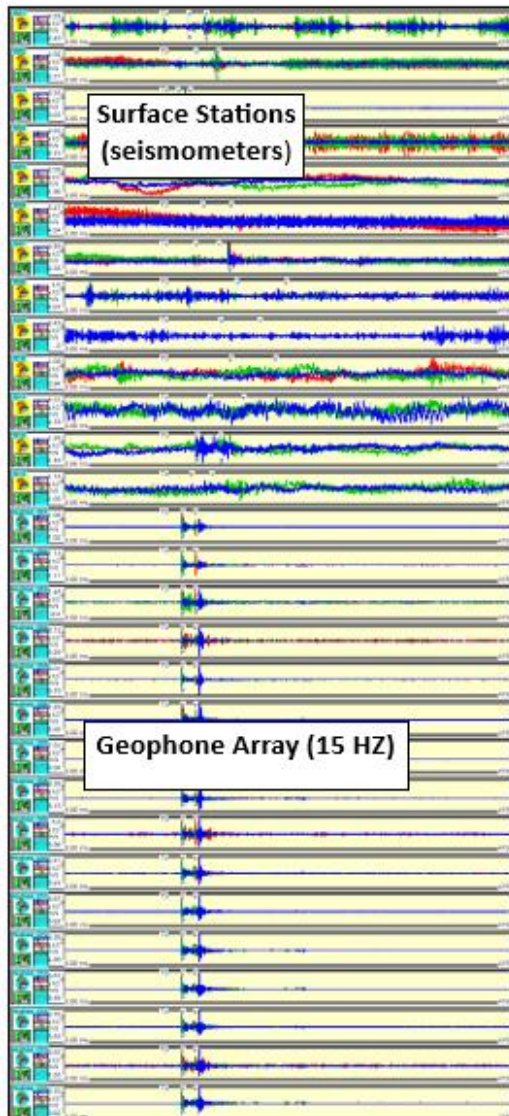
A shallow (~500m) geophone array enables the detection of $M_w \approx -1$ events, which is often sufficient for trend analysis in CCUS injection monitoring. Alternatively, a deep geophone array, positioned near but not penetrating the injection formation, is beneficial for caprock integrity assessments, fault monitoring, and abandoned well migration detection. Combining high- and low-frequency sensors in either configuration enhances the accuracy of magnitude and source parameter estimations for induced seismic events.

Geophone arrays offer superior sensitivity for detecting microseismic events compared to Fiber Optic DAS, particularly for low-magnitude events. However, incorporating Fiber Optic DAS as the downhole component enhances depth accuracy and provides slightly improved event detection due to its continuous spatial coverage along the fiber. While Fiber Optic DAS is capable of detecting microseismic activity, its sensitivity is lower than that of geophones, since microseismic events are generally less frequent in proximity of the injection well.

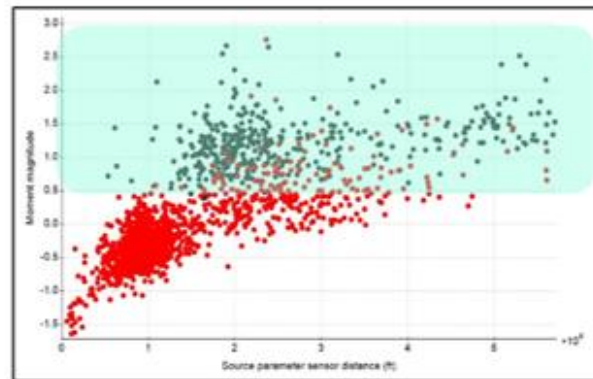
Case study 1: Hybrid Monitoring -Private Seismometer Network with Downhole Geophone Array

Figure 2 illustrates a hybrid seismic monitoring system, integrating a private surface seismometer array with a downhole geophone array, to monitor seismic events from a subsurface injection operation. Figure 2a displays waveforms recorded at different stations for a seismic event. The downhole geophone array is more sensitive to higher-frequency signals, making it particularly effective for detecting low-magnitude microseismic events. In contrast, surface stations record a broader frequency spectrum, but high-frequency signals experience greater attenuation as they travel through the subsurface. As shown in Figure 2b, the downhole geophones primarily detect small-magnitude events (red cluster), especially at shorter distances. In comparison, the hybrid system (black points) extends the detection range, allowing for the identification of larger events at greater distances. The green-shaded area represents the magnitude range predominantly captured by the hybrid system, which is notably more restricted than the downhole geophone array, particularly in detecting smaller-magnitude events. Depth histogram of seismic events is presented in Figure 2c. The event distribution pattern suggests that seismic activity is clustered around the injection interval, with fewer deep-seated events. Enhanced location accuracy achieved through hybrid monitoring improves the characterization of the reservoir response to injection, enabling more efficient monitoring of induced seismicity and the implementation of mitigation strategies when necessary.

a)



b)



c)

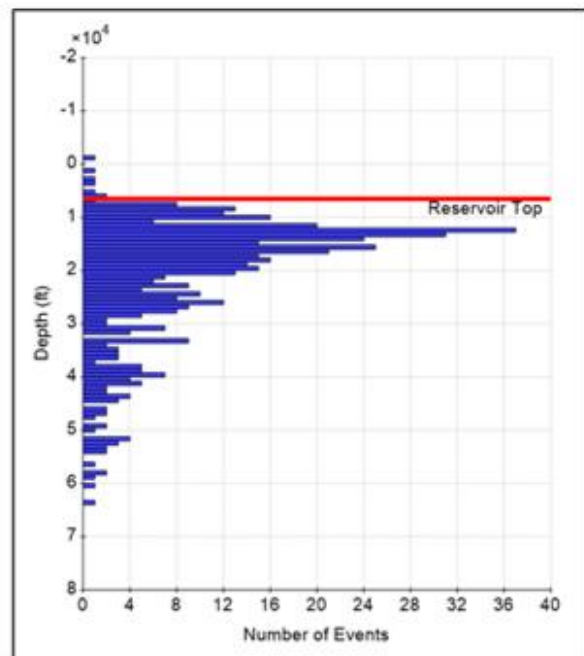


Figure 2: Hybrid seismic monitoring system, integrating a private surface seismometer array with a downhole geophone array, to monitor seismic events from a subsurface injection operation. a) Waveforms recorded at different stations for a seismic event. Events recorded at surface stations (seismometers) are labelled at the top, and events recorded by downhole geophones are labelled at the bottom. The downhole geophone array captures higher-frequency signals, which are important for detecting low-magnitude microseismic events. The surface stations capture broader frequency ranges, but with more attenuation of high-frequency signals due to propagation effects. b) Magnitude vs. distance scatter plot. In this plot red points correspond to detections from the downhole geophone array, and black points represent data from the hybrid system (surface + downhole). The downhole geophones detect more small-magnitude events (red cluster), particularly at closer distances. In contrast, the hybrid system (black points) extends the detection range and captures larger events at greater distances. The green-shaded area highlights the magnitude range primarily detected by the hybrid system, which is significantly more limited compared to the broader detection capability of the downhole geophone array, particularly for smaller-magnitude events. c) Depth histogram of seismic events. The x-axis represents the number of detected events, and the y-axis represents depth in ft. The red line labelled "Reservoir Top" marks the upper boundary of the injection formation. The event distribution pattern suggests that seismic activity is clustered around the injection interval, with fewer deep-seated events. Source: ESG Solutions (2025).

Case Study 2: Hybrid Monitoring – Private Seismometer Array with Downhole Fiber (DAS)

Figure 3 shows a hybrid seismic monitoring approach combining a private seismometer array (surface stations) with downhole Distributed Acoustic Sensing (DAS) fiber to detect and characterize seismic events. The waveform panels illustrate different seismic sources, including a blast event (left panel), a distant earthquake (middle panel), and a regional or distant earthquake observed on DAS (right panel). This hybrid setup enhances spatial coverage, improves event detection, and provides additional insights into seismic wave propagation through the subsurface.

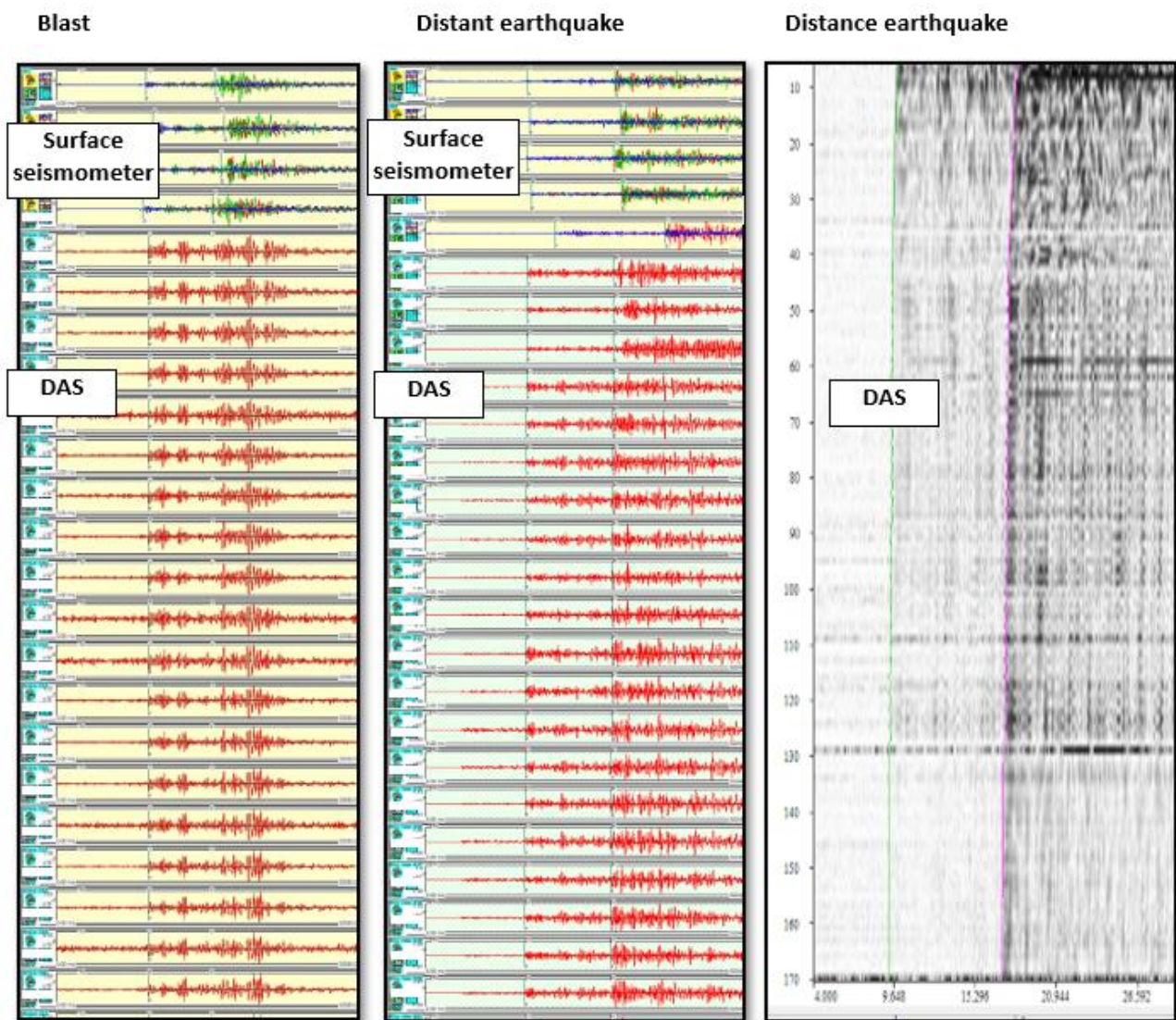


Figure 3: Hybrid monitoring using private seismometer array with downhole fiber (DAS). In the left panel, surface seismometers and DAS recordings show high-frequency waveforms characteristic of a blast. The DAS fiber captures waveforms with higher resolution along its length, making it particularly effective for detecting localized, high-energy sources. Seismometer waveforms display broader frequency content, but with lower spatial resolution than DAS. The middle panel presents a regional (distant) event. Seismic energy from the distant event is clearly recorded by both the surface seismometers and DAS. The DAS fiber provides continuous spatial sampling, allowing for detailed tracking of wave

propagation through depth. The right panel illustrates the regional event detected on DAS. The data shows strain rate variations over time and depth. Two seismic phases are clearly visible, indicating that DAS can distinguish between P-waves and S-waves as they propagate along the fiber, enabling real-time tracking of seismic wave arrivals. Source: ESG Solutions (2025).

Case Study 3: Fiber Optic DAS Resolution

Figure 4 presents the results of a case study in the U.S. that utilized DAS technology for microseismic monitoring during a hydraulic fracturing operation. DAS captured seismic signals along fiber optic cables deployed in two horizontal wellbores. The scatter plot visualizes detected seismic events, with moment magnitudes ranging from M_w -1.25 to 0.5, plotted against the source parameter sensor distance. As expected, seismic event density is highest near the sensor and gradually decreases with increasing distance. The DAS captured M_w -0.5 up to 3,500 ft from the DAS cable, with many single phase microseismic events not displayed in the below plot, which likely could have been captured by geophones.

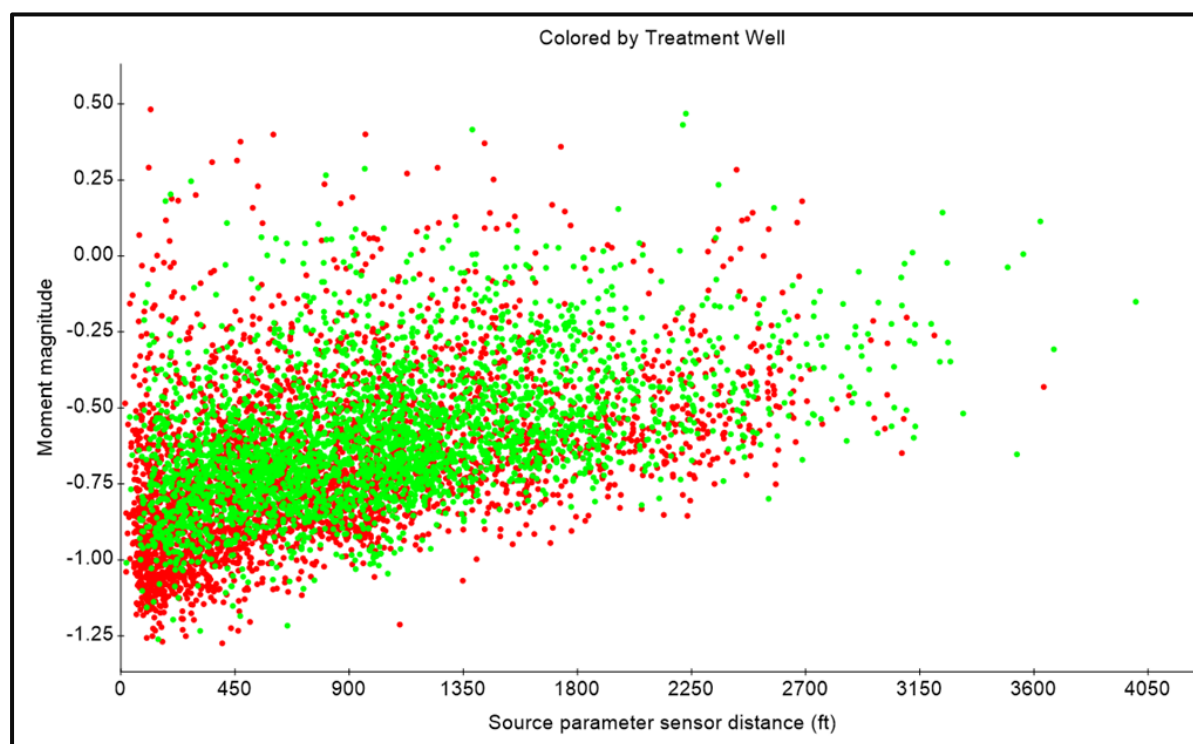


Figure 4: Results of a case study in the U.S. utilizing DAS technology for microseismic monitoring. Dots represent detected microseismic events in two horizontal wells. The minimum detectability threshold of M_w -1.25.

Case Study 4: Trend Delineation

Understanding microseismic-scale seismicity plays a crucial role in risk mitigation by identifying trends and stress changes, allowing it to function as an early warning system. Additionally, analyzing stress variations can help validate geological features identified through other geophysical techniques, such as seismic imaging. In a CCUS project in North America, microseismic data detected by a downhole geophone array, revealed regional stress variation trends, which were instrumental in redefining the project's Area of Review to enhance monitoring and risk assessment.

Figure 5 illustrates moment magnitude over time, indicating a delayed seismic response following CO₂ injection, likely due to gradual pore pressure diffusion and stress accumulation. The absence of recorded seismicity before injection suggests a low background seismic activity in the region. After injection begins, microseismic activity increases, with periodic spikes in magnitude, indicating episodes of stress accumulation and release.

Figure 6 presents a map view of seismicity associated with the CCUS project, illustrating the distribution of seismic events relative to three injection wells. Localized stress concentration is evident within 10 km of the injection wells, where microseismic activity is most pronounced. Additionally, stress rotation over a larger area is observed, with higher-magnitude events occurring at greater distances. The expansion of seismicity suggests regional stress transfer, potentially linked to fault activation. The delayed seismic response and evolving stress patterns are likely influenced by gradual pore pressure diffusion and progressive stress perturbation.

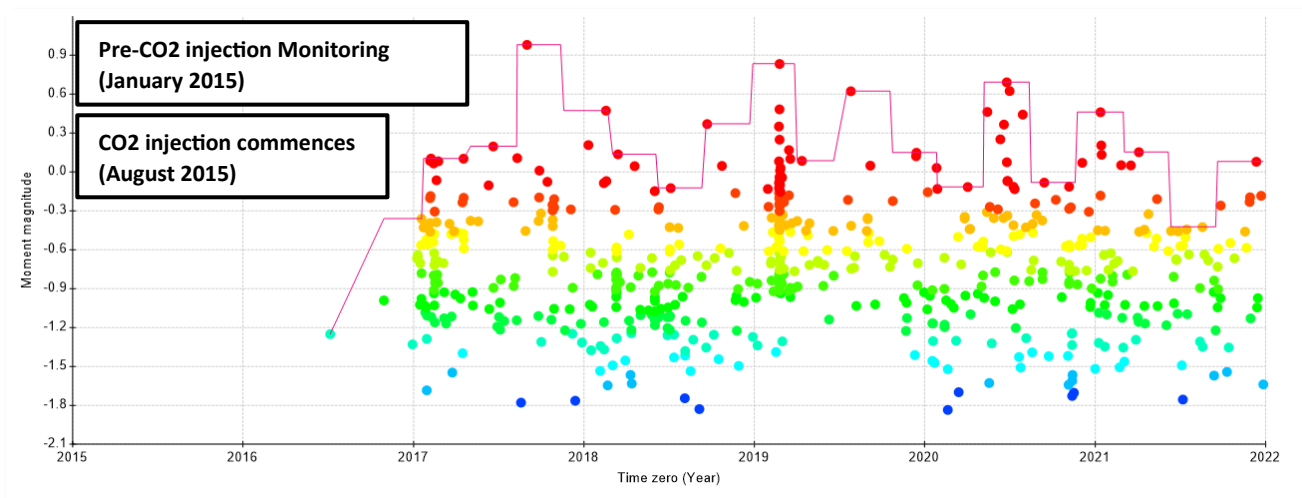


Figure 5: Moment magnitude over time from a CCUS project in North America, recorded using a downhole geophone array with 15 Hz geophones. Data points are color-coded by moment magnitude, while the envelope represents the maximum magnitudes over time. The observed delayed seismic response following CO₂ injection is likely related to gradual pore pressure diffusion and stress accumulation. Post-injection, microseismic activity increases significantly, with periodic spikes in magnitude, suggesting episodic stress accumulation and release. Source: ESG Solutions (2025).

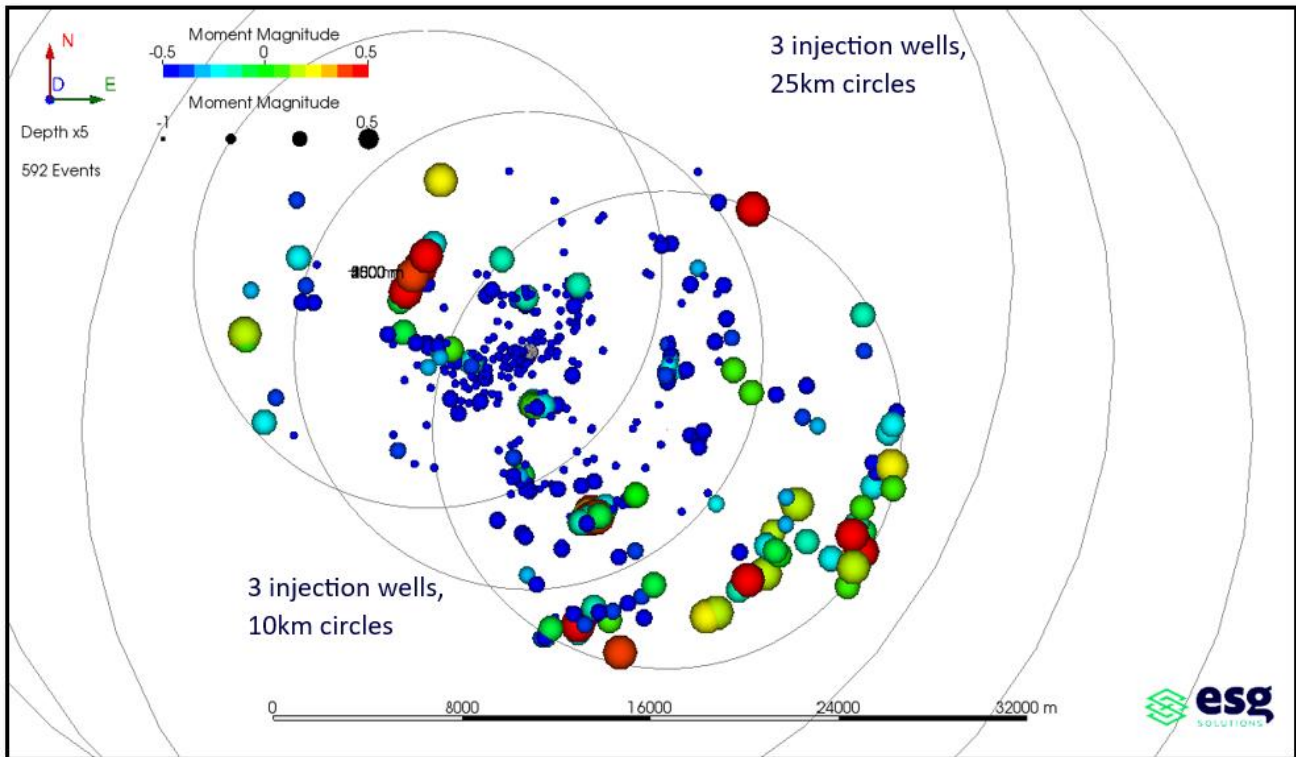


Figure 6: Map view of the seismicity associated with the CCUS project. Large number of events indicates a significant seismic response to injection. Events are color-coded by moment magnitude with blue and green dots representing lower-magnitude microseismic events and yellow to red dots indicating larger events (closer to $M_w = 0.5$). The presence of larger-magnitude events (red and yellow dots) farther from the injection wells suggests regional stress redistribution, possibly due to pore pressure diffusion or fault interactions. Source: ESG Solutions (2025).

Case Study 5: Casing Failure & Caprock Integrity

Figure 7 shows an explosive casing failure event and associated microseismic activity breaking through the caprock, captured using a downhole geophone array (15 Hz geophones). Figure 7a displays waveform data from multiple geophone sensors along the wellbore, alongside a 3D visualization of event location. Figure 7b presents a spatial distribution of microseismic events in M_w , highlighting clusters associated with the casing failure.

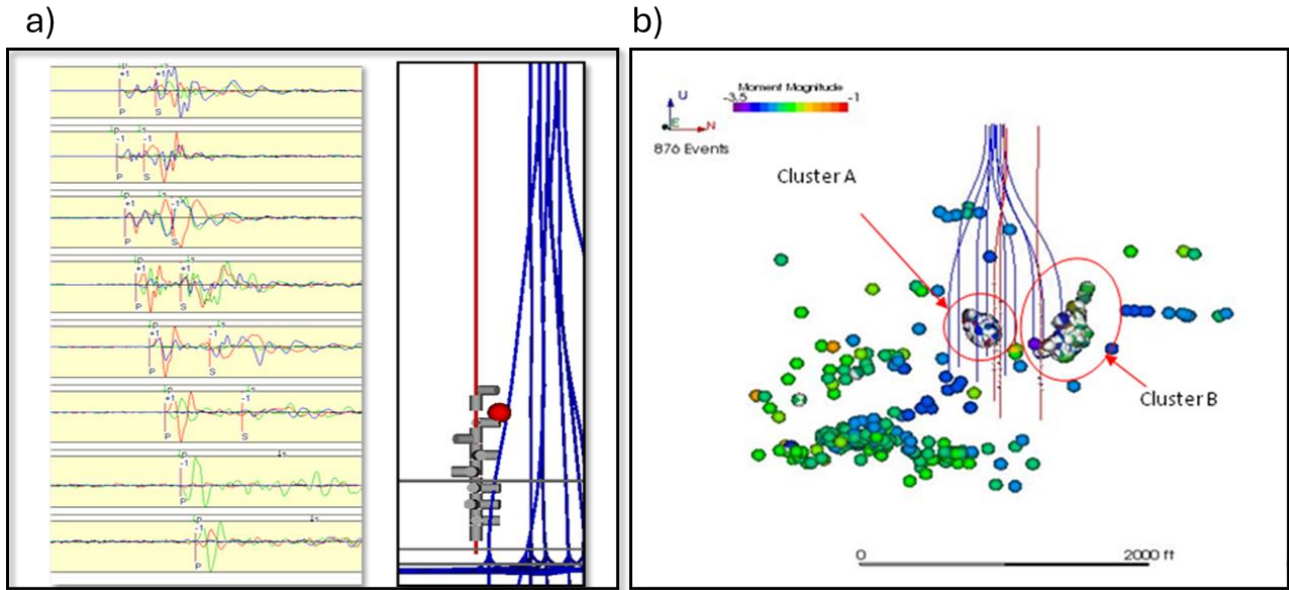


Figure 7: Casing failure event and associated microseismic activity breaking through the caprock. a) Seismic waveforms recorded at different depths along the wellbore. Clear P-wave and S-wave arrivals are marked, showing a consistent onset pattern across multiple sensors, which helps in accurate event localization. Some waveforms show high-amplitude signals, indicating a strong energy release. The blue lines represent well trajectories and the red circle marks the seismic event, highlighting its depth and proximity to the casing. b) Map view of seismic events, color-coded by moment magnitude. Two distinct seismic clusters (cluster A and cluster B) are identified, both associated with the casing failure. Source: ESG Solutions (2025).

Conclusions

Subsurface injection is widely recognized as a potential driver of induced seismicity, necessitating robust monitoring to assess stress variations associated with injection operations. The integration of surface seismic stations with a downhole monitoring component, such as fiber optic Distributed Acoustic Sensing (DAS) or downhole geophones (shallow or deep), significantly enhances event detection capability and reduces depth uncertainty. These improvements provide a more comprehensive understanding of stress evolution, enabling operators to make data-driven decisions for risk mitigation and operational adjustments. A well-designed hybrid monitoring system ensures early detection of anomalous seismicity, facilitating proactive measures to maintain reservoir integrity and regulatory compliance in subsurface injection projects.

References

- Babaie Mahani, A., and H. Kao (2019). Accurate Determination of Local Magnitude for Earthquakes in the Western Canada Sedimentary Basin, *Seismological Research Letters*, Vol. 90, No. 1, p. 203-211.
- Bethmann, F., N. Deichmann, and P. M. Mai (2011). Scaling relations of local magnitude versus moment magnitude for sequences of similar earthquakes in Switzerland, *Bull. Seismol. Soc. Am.* 101, 515–534.
- Edwards, B., B. Allmann, D. Fah, and J. Clinton (2010). Automatic computation of moment magnitudes for small earthquakes and the scaling of local to moment magnitude, *Geophys. J. Int.* 183, 407–420.
- Hanks, T. C., & Kanamori, H. (1979). A moment magnitude scale. *Journal of Geophysical Research: Solid Earth*, 84(B5), 2348-2350.
- Kanamori, H. (1977). The energy release in great earthquakes. *Journal of geophysical research*, 82(20), 2981-2987.
- Nicol, Andy & Seebeck, H. & McNamara, David & Field, B.. (2016). Fault Permeability.
- Ross, Z. E., Y. Ben-Zion, M. C. White, and F. L. Vernon (2016). Analysis of earthquake body wave spectra for potency and magnitude values: Implications for magnitude scaling relations, *Geophys. J. Int.* 207, 1158–1164.
- Silver, P. G., & Jordan, T. H. (1982). Optimal estimation of scalar seismic moment. *Geophysical Journal International*, 70(3), 755-787.
- Yenier, Emrah. (2017). A Local Magnitude Relation for Earthquakes in the Western Canada Sedimentary Basin. *Bulletin of the Seismological Society of America*. 107. 10.1785/0120160275.