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Assessing the effect of velocity model accuracy on microseismic interpretation at the In Salah carbon capture and storage site

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Abstract

Injection of carbon dioxide (CO_2) to be stored at depth at the In Salah Carbon Capture and Storage (CCS) site began in 2004 with the subsequent installation of a pilot microseismic monitoring well in 2009. The project is one of only two industrial-scale storage projects to have been monitored for microseismicity. Such projects are vital to demonstrate the validity of CCS technology and the role of microseismic monitoring, a technology that could be used in real-time to regulate the geomechanical response of a site to CO_2 injection.

Substantial microseismicity (over 9000 events) was recorded by a single three-component geophone situated at 80m deep almost directly above one of the In Salah injection wells. The events occur in two main clusters with estimated locations of well-recorded events within one of these clusters to be within 1km horizontal distance from the geophone and between 2.1km and 2.7km deep, at least 200m below the injection depth and CO_2 storage interval. Errors in the depth range of event locations are investigated using modified velocity models, revealing that 10% slower velocities create uncertainties up to 450m in depth. Alternatively, 20% slower velocities in the shallow sub-surface or an anisotropic model have a similar effect. Independent of the absolute depth, there is no migration of event locations to shallower depths with time. Evidence from the analysis of shear-wave splitting delay times implies that, between 2009 and 2011, CO_2 injection is opening pre-existing fractures that then close as pressure decreases, rather that creating new fractures. The estimated dominant fracture orientation is approximately NW-SE, in agreement with fracture orientations inferred from logging data, and the observed maximum moment magnitude, $M_W = 1.7$, is also consistent with estimated pre-existing fracture dimensions at the injection depth.

This work demonstrates the value of microseismic monitoring of CCS projects, even with a limited array, but an accurate velocity model is critical to allow reliable interpretation of the data. We recommend that microseismic monitoring is conducted prior to CO_2 injection at future CCS sites to enable baseline and comparative studies. Real-time microseismic monitoring would help inform injection decision and contribute to the safe operation of a project.

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1. Introduction

Large-scale Carbon Capture and Storage (CCS) projects, where CO_2 is injected into the ground to be stored at depth, is an important area of developing technology aiming to reduce anthropogenic CO_2 emissions and mitigate global warming. For the technology to be safe and effective, injected CO_2 must remain trapped for thousands of years. To date, however, few large-scale projects have been realised and many questions remain about how sites will respond geologically and geomechanically to the injection of millions of tons of supercritical CO_2 at up to several kilometres depth. Understanding a site's geomechanical response to CO_2 injection is key to ensuring safe CO_2 storage and, even though only a small number of CCS projects exist, it has been observed that effect of injection is very different depending on the geological setting [1].

One concern for CO_2 storage security is the potential for such projects to induce earthquakes [2]. Induced seismicity may result from the reactivation of pre-existing faults or fractures, or from the generation of new fracture networks. Any activated faults and fractures could act as leakage pathways for CO_2 so accurate knowledge of the location of any induced seismicity is particularly important. Microseismic activity in the CO_2 injection interval is very unlikely to pose a problem for safe storage. Large events or seismic activity in the caprock or overburden require detailed investigation. The accuracy of computed event locations depends on the velocity model used to calculate seismic wave travel-times and also on the recording instrumentation. It is therefore vital to the seismic interpretation that velocity models are well known. The theoretical effect of velocity model accuracy on event locations has been discussed previously (e.g., [3] and [4]) and in the present study we look at the effect model errors may have on the interpretation of the microseismic data recorded at In Salah. In addition, we review the microseismic activity at the site to aid understanding of the geomechanical response and investigate the possibility that CO_2 injection caused fracturing in the reservoir.

2. Monitoring the In Salah CO_2 storage site

The In Salah Joint Venture carbon capture and storage (CCS) project at Krechba, Algeria began injecting CO_2 in 2004 into the water leg of a 20 – 25m thick reservoir at ~1880m deep, overlain by a ~950m thick Carboniferous mudstone caprock (Fig. 1). During the first 5 years of injection InSAR (Interferometric Synthetic Aperture Radar) studies detected several cm of surface deformation above the injection wells ([5] and [6]). These authors report conclusions in agreement with those of the 2009 3D seismic survey suggesting that CO_2 injection resulted in the opening of a deep fracture zone, parallel to the dominant NW-SE fracture orientation [7], and extending NW of injection well KB-502, several hundred metres wide and extending about 150m above the reservoir [8].

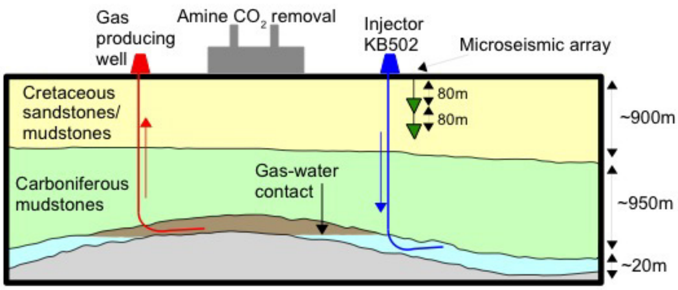


Fig. 1. Schematic illustration of the geology of the Krechba field. The position of microseismic array and the geophones used in this study (green triangles) are indicated also indicated.

In 2009 a pilot vertical array of geophones were installed in a well almost directly above the horizontal extension of injector KB-502 (Fig. 1). Six three-component (3C) 15Hz geophones between 80m and 500m deep were connected and recorded continuous data at 500Hz until June 2011 [9]. Unfortunately, due to technical issues (e.g., non-functioning channels, cabling problems and malfunctioning GPS units), it has only been possible to orientate and confidently process the data from one 3C geophone, the uppermost instrument at 80m deep. In addition the vertical component of the geophone at 160m deep provides reliable data.

3. Initial event location estimates

We use the two reliable vertical components of data to detect events using cross-correlation methods similar to those described in [10]. Using this method, 9506 microseismic events are detected between August 2009 and June 2011 and subsequently we pick 6280 S-arrivals by hand. These events correlate with injection rate (Fig. 2), particularly during extended periods of high injection rates (e.g., April to July 2010) and when injection ceases the rate of seismic events drops quickly <10 events/day. The travel-time differences between the microseismic S- and P-arrivals, t_{sp}, are grouped into two main clusters, Cluster 1 with t_{sp}≈0.68s and Cluster 2 with t_{sp}≈0.95s, that occur mainly to the NW and SE of the array (Fig. 3). The receiver-source distance of Cluster 1 changes slightly during periods of high injection, illustrated by an increased range of t_{sp} to 0.6s – 0.8s. Both clusters contain events with very similar waveforms, most with cross-correlation coefficients > 0.8. To estimate the source-receiver direction we perform P-wave particle motion analysis, following [11]. P-arrival particle motion is linear in the direction of propagation so the vector defined by the azimuth and inclination (angle from vertical) of the incoming P-wave points in the receiver-to-source direction.

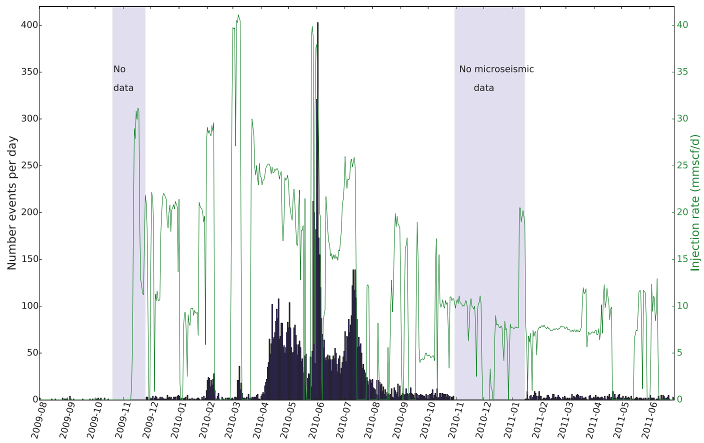


Fig. 2. Histogram of microseismic events detected at In Salah throughout the monitoring period. The injection rate is illustrated by the green line.

Due to ray-bending in a layered velocity model the measured P-wave incidence angles, i_o, are not the same as the geographical incidence angle, i_g, from the receiver to the source. We use an eikonal solver to produce model event locations for a range of t_{sp} and a sample of the resulting grid of locations is given in Fig. 4a. We produce synthetic waveforms for these grid points using the E3D finite difference code, a 3-D elastic seismic wave propagation code [12], and a 1-D layered velocity model. We measure i_o on the synthetic waveforms and compare these to the i_g of the grid locations and find that, for 0.60s < t_{sp} < 0.80s (the lower and upper bounds for Cluster 1 – see Fig. 3), $i_g - i_o < 5°$ for $i_o < 15°$ (Fig. 5).

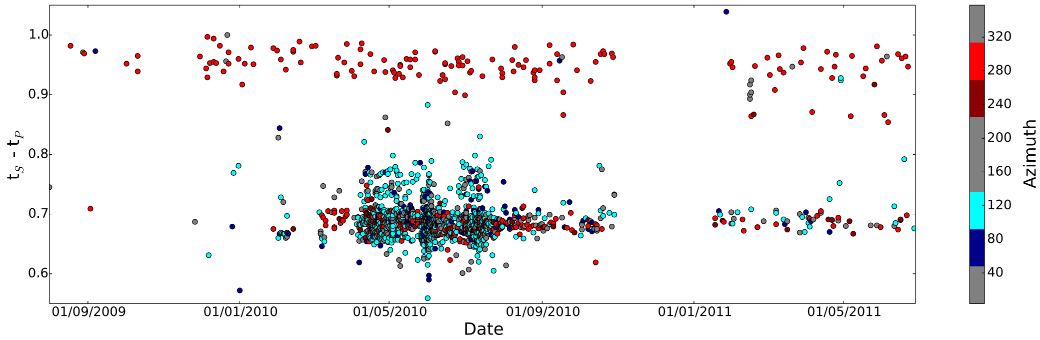
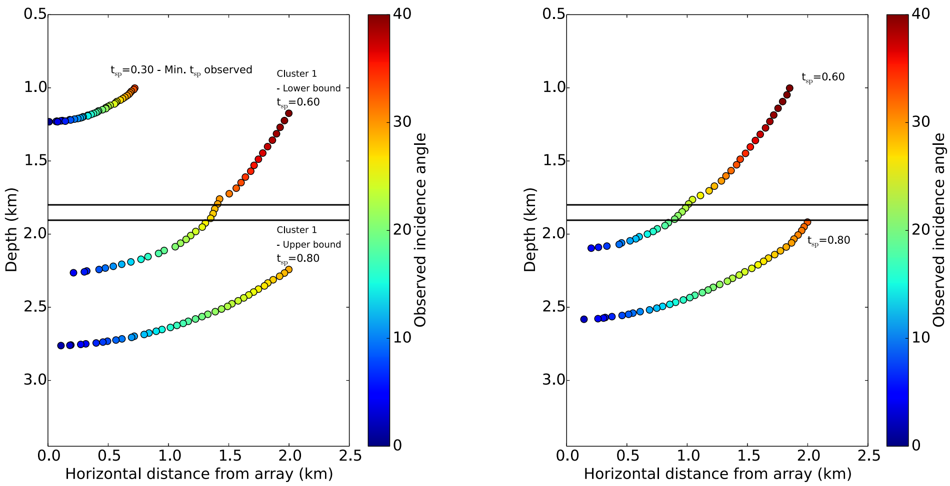


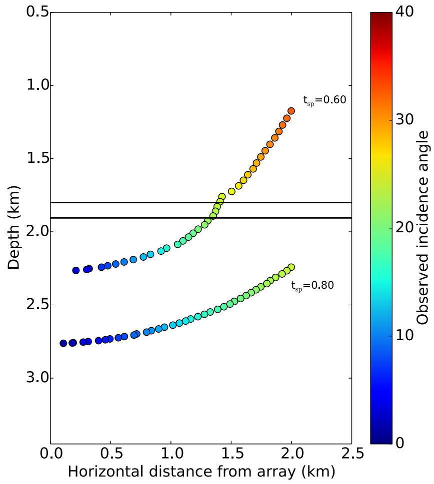
Fig. 3. Events in Clusters 1 (t_{sp}≈0.68s) and 2 (t_{sp}≈0.95s) as a function of the time between S- and P-arrivals. The colours indicate the receiver-source azimuth.

To estimate microseismic event locations we carefully select the events with the most reliable recordings. For quality control we measure the linearity of the P-wave particle motion ([11], [13]) and only consider events with linearity >0.95 (the linearity is 1 for perfectly linearly polarised P-waves). For additional quality control we only estimate event locations for arrivals with i_o<15° and t_{sp}<0.85s to limit errors in estimated locations that could be caused by small errors in the measured inclination angles. The resulting 1610 event locations are displayed in Fig. 6, placing the events at between 2.1km and 2.7km deep and at least 200m below the injection interval. We also conduct a ray-tracing exercise to estimate event locations using the method of [14] and the isotropic 1-D velocity model. This places events with 0.60s < t_{sp} < 0.80s at ~2400m deep and 0.0km – 2.0km horizontal distance from the array (Fig. 7a), similar to the estimated locations obtained through finite-difference modelling.



a) Original 1D isotropic velocity model

b) Velocities 10% slower than original model



c) Uppermost 150m 20% slower than original model

Fig. 4. Event depths and horizontal distances from the observation well for different t_{sp} times, estimated using E3D. The colours represent the inclination of the P-arrival measured from the synthetic waveforms. The approximate injection interval is between the two thicker black lines at ~1.9km deep.

It is surprising that the reported event locations are below the injection interval, it is expected that events would occur mainly in the fractured reservoir or potentially in the caprock if there is vertical migration of CO_2 or events caused by stress transfer. We therefore investigate what effect potential inaccuracies in the velocity model have on the estimated locations.

4. Anisotropy and fracture characteristics

First we look for evidence to confirm whether an anisotropic velocity is realistic for this site. Shear waves are split into a fast and a slow wave in anisotropic media and shear-wave splitting analysis can be used to characterise anisotropy and infer fracture strike and degree of anisotropy (e.g., [15], [16] and [17]). Anisotropy in seismic velocities arises in rocks when aligned fracture sets are present with sizes and spacing smaller than the dominant wavelength (e.g., [18]). The fast wave is polarized in the orientation of the dominant fracture orientation, ϕ, and the time difference between the fast and slow waves provides a measure of the degree of anisotropy, δt. As reported in [19], we find the dominant fracture strike, 140° – 160°, is consistent with the results from logging data [7] and fracture modelling [20]. The lower limit of δt remains constant at 0.030s between 2009 and 2011 but the upper limit increases from 0.045s to 0.058s during periods of high injection. To determine the significance of the observed shear-wave splitting we estimate the strength of anisotropy using the common approximation:

$$A = {}^{100 * V_{Smean}\delta t}\!/_{r}, \qquad (1)$$

where r is the source-receiver-distance, V_{Smean} is the mean S-wave velocity and δt is the delay in arrival time between waves polarized along the fast and slow symmetry axes. Assuming δt = 0.03s, A≈3%. We therefore include an anisotropic velocity model in our assessment of the effect inaccuracies in the velocity model could have on event locations at In Salah.

We suggest that the observed change in δt with injection rate indicates that high injection rates are opening pre-existing fractures, resulting in an apparent increase in fracture density, that then close as pressure decreases. These results do not rule out the possibility that injection prior to August 2009 created new fractures or that fractures were created after August 2009 that these raypaths do not sample. Our estimated maximum moment magnitude for the events is M_W=1.7. This values provides reassurance that no major faults are being activated because it is consistent with the larger fractures estimated from logging data by [7] and therefore is within the range that could be expected from pre-existing fractures in the reservoir.

5. Velocity model effect on locations

To assess the effect errors in the velocity model could be having on our interpretation of the microseismic data at In Salah we look at changes in estimated event locations using three altered velocity models. The models reported here are chosen so that events at reservoir depth and within 2km of the array are predicted to have $t_{sp}\lesssim0.7$s. Relative to the original 1D model these altered models are

a) 10% slower overall,
b) the uppermost 150m is 20% slower,
c) an anisotropic model containing vertical cracks with density $0.05m^{-1}$ and aspect ratio 0.005, representative values taken from the work of [7]. It is also assumed the fractures are filled with supercritical CO_2 that reduces the P- and S-wave velocities by 10% as have been observed in laboratory experiments [21].

Using models (a) and (b) we conduct finite-difference modelling and use an eikonal solver to estimate locations as described in Section 3 above. We also carry out ray-tracing experiments, as above, with all three altered models. The ray-tracing through these models places events with t_{sp}=0.68s at 1.9km – 2.0km deep and at 1.4km – 1.7km horizontal distance from the array (Figs. 7b – d) while the finite-difference results show a slightly different picture (Figs. 4b – c). Reducing the velocities by 10% places the events displayed in Fig. 6 between 1.9km and 2.5km deep but reducing the velocity in the near-surface does not significantly affect the locations.

Thus the use of velocity models within realistic bounds places the events up to 450m shallower than the depths obtained with the original 1D model. This would place the events in the depth range 1.65km – 2.25km, in agreement with the inferred opening of a fracture zone extending about 150m above the reservoir [8]. The changes made to the velocity model in these experiments are significant but not unrealistic. 10% errors in velocity models are common, particularly in areas with industrial or volcanic fluid injection and near-surface velocities can vary with ground water changes.

6. Discussion

The microseismic data from the In Salah CCS site should be useful in the planning of future CCS projects in terms of how a site is monitored. The project is only the second >1Mt storage project to be monitored using a microseismic array and the results presented above illustrate the usefulness of the data in understanding the geomechanical response of the site to CO_2 injection. The main advantage of microseismic monitoring over other geophysical techniques, such as 4D seismic reflection and InSAR, is that the data can be processed in real-time and can therefore provide an early warning system for CO_2 leakage or fault reactivation, if event locations can be accurately determined.

Central to this aim of accurate event locations is the availability of an accurate velocity model. Locations computed using the given 1D velocity model for this site place well-recorded events at >200m below the injection depth. Intuitively we expect events to occur at the injection depth, potentially spreading out to shallower and deeper locations depending on the injection rate and geological setting. This would be true for events detected at In Salah if the actual velocity model is slower than the given model and/or if velocities are anisotropic at the site. Results from our ray-tracing experiments suggest the absolute errors in depth in this case are of the order of 400m (Fig. 7).

Multi-sensor arrays (>5 instruments) covering a wide aperture are required to allow accurate event locations to be calculated. The information that can be gained from the In Salah microseismic data is limited because only one 3C geophone provides reliable data. We show, however, that a single, shallow instrument can be useful in monitoring CCS sites but further studies providing more accurate, precise and reliable information would be possible if a more extensive array were deployed. We find the microseismicity at In Salah occurs in two main clusters oriented approximately NW-SE from the array. The depth of these clusters is uncertain but our results, including the possibility of significant systematic errors in the velocity model, place the estimated depth range of a well-recorded subset of events between up to 150m above the reservoir and almost 1km below the injection depth (1.65km – 2.7km deep).

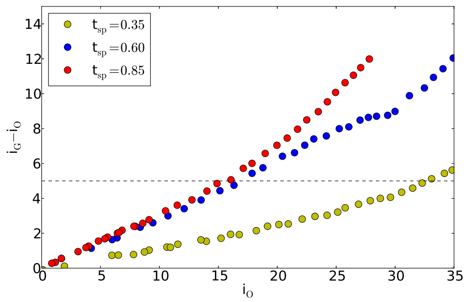


Fig.5. Difference between the geographical, i_g, and observed, i_o, incidence angles of P-arrivals as a function of i_o.

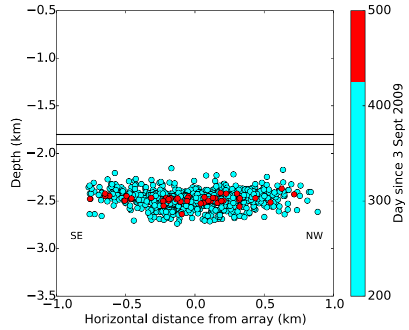
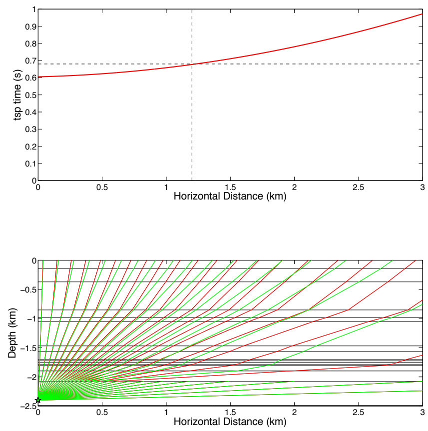
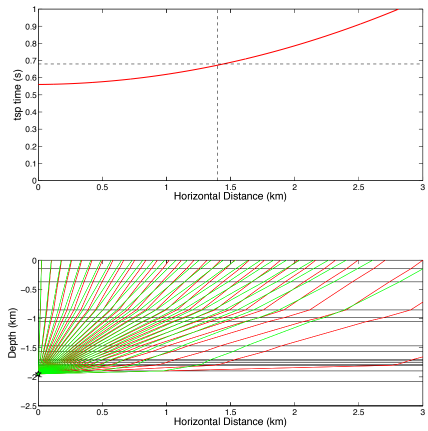


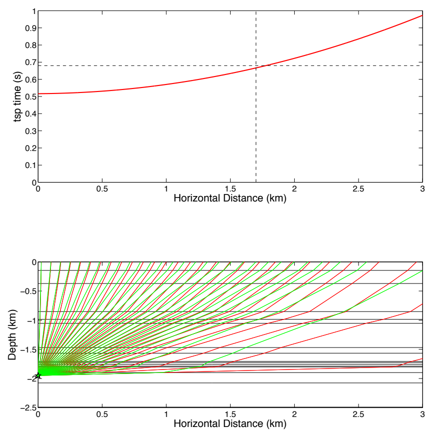
Fig. 6. Estimated event locations, depth and horizontal distance from the microseismic array in the SE-NW direction, for events satisfying the condition linearity > 0.95 and $i_g - i_o < 5°$. Cyan colours are events occurring until November 2010. Red colours are events in 2011.



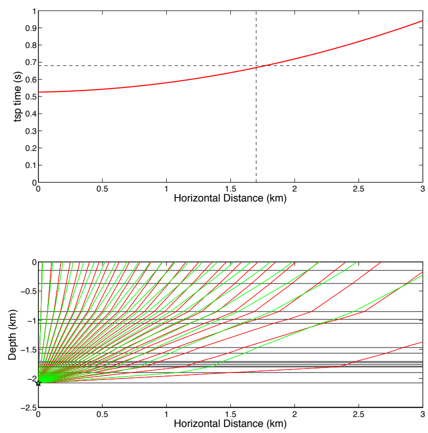
a) Original 1D velocity model



b) 10% slower than original velocity model.



c) Near-surface 20% slower than original model



d) Anisotropic model

Fig. 7. Upper panels show S – P arrival times, t_{sp}, as a function of horizontal distance for various velocity models. Lower panels show ray-tracing of P- (red) and S-waves (green) are shown with the source given by the green star.

During the first half of 2010, when the injection rate and event rate were high, the depth range covered by the well-recorded events is ~600m (cyan colours in Fig. 5). Later in the sequence, in 2011 (day > 500) when the injection rates are low, the events are restricted to a range in depths of ~250m (red colours in Fig. 5). Although there are errors in absolute depths reported here, the relative depths show that high injection rates stimulate a larger volume to become seismically active, as we might expect. The large number of events and the high degree of similarity between the waveforms within the clusters ([19] and [22]) makes it likely that events occur on a dense network of fractures with very similar orientations. The finite-difference modelling results suggest there may be a few events (11) occurring above the injection interval but we do not observe any evidence for migration of seismicity through the caprock with time. This supports the conclusion that CO_2 containment can be assured at this site.

From shear-wave splitting analysis we obtain ~3% anisotropy and a dominant fracture orientation NW-SE. This is consistent with the observations of the pre-existing dominant fracture orientation reported from borehole logging data. The maximum estimated moment magnitude of M_W=1.7 is also consistent with the fracture dimensions estimated from the borehole data. There is some evidence from shear-wave splitting delay times that pre-existing fractures are opening during periods of high CO_2 injection rates, thereby increasing the degree of anisotropy. The delay times return to the original values when injection rates fall, indicating a closure of fractures as pressure reduces. This supports the conclusions of previous InSAR and 3D seismic studies (e.g., [5] and [8]) that CO_2 injection resulted in the opening of a pre-existing fracture zone running NW-SE and spanning the injection depth.

7. Conclusion

Through our analysis of data recorded on a single 3C geophone at the In Salah CO_2 sequestration site we observe thousands of events between 2009 and 2011. Our estimates of locations for a subset of these events suggests they are located in a cluster oriented approximately NW-SE of the microseismic array and at least 200m below the injection interval. Investigations into the effect of velocity model accuracy on locations at the site suggest that these events could be located at the injection interval if the velocity is 10% slower overall, if the uppermost 150m are 20% slower or if velocities are anistropic. Our estimated event locations and observations of shear-wave splitting parameters are consistent with seismicity occurring on a pre-existing fracture zone containing fractures oriented NW-SE that open when CO_2 injection rates are high. Even though the instrumental set-up and data reliability place constraints on the conclusions we are able to draw from the microseismic data, our analysis shows that events are likely occurring along a pre-existing NW-SE oriented fracture zone close to the injection well. We also note that the seismicty rate drops off rapidly once injection stops. This supports the contention that seismicity could be controlled by careful control of injection pressures.

Microseismic monitoring at the In Salah site was only implemented as a pilot study five years after CO_2 injection began and therefore we cannot make any assertions regarding the microseismicity or fracture characteristics before August 2009. It is an important point for future projects that, with baseline microseismic data and monitoring when injection began, it would have been possible to gain a much fuller understanding of the geomechanical response of the site to CO_2 injection and it is likely that microseismic data would have highlighted the activation of the fracture zone before it could be detected using other techniques. This study shows that useful information can be gained from microsismic data to help regulate injection parameters and thus site response to CO_2 injection.

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