Adaptive moment-tensor joint inversion of clustered microseismic events for monitoring geological carbon storage

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1 INTRODUCTION

Microseismic moment-tensor inversion can provide valuable information of microseismic events for monitoring CO₂ injection (Gan & Frohlich 2013; Verdon et al. 2015), wastewater injection (McNamara et al. 2015), hydraulic fracturing (Rutledge et al. 2004; Sileny et al. 2009; Maxwell 2014) and geothermal reservoirs (Ross et al. 1996; Julian et al. 2010; Zhao et al. 2014). Microseismic moment-tensor inversion allows us to monitor fluid movement, evaluate geomechanical responses, understand the physical process of fracturing to fracture activation, and assess potential fluid-injection-induced earthquake hazards. A wide-azimuthal coverage of geophones is generally essential for accurate moment-tensor inversion. However, for cost-effective and typical hydrocarbon or unconventional oil/gas microseismic monitoring, often only one vertical-borehole geophone array is used to detect low-magnitude events (Soma & Rutledge 2013). The receiver-array geometry plays a fundamental role in the stability of the inversion (Eaton & Forouh pedigree 2011). A limited azimuthal coverage of geophones leads to large moment-tensor inversion uncertainties (Vavrycuk 2007; Rodriguez et al. 2011). For example, a single vertical-borehole geophone array is not adequate for inverting six components of moment tensor of a microseismic event (Nolen-Hoeksema & Ruff 2001; Vavrycuk 2007). Microseismic data collected in a noisy environment can further increase inversion uncertainties and yield inaccurate inversion results.

Injecting CO₂ into oil reservoirs to enhance oil recovery is a primary approach to carbon utilization and storage. CO₂ injection can change geomechanics of the injected reservoirs and nearby formations, create or re-activate pre-existing faults/fractures and could result in CO₂ leakage through reservoir caprock and faults/fractures (Rutqvist et al. 2008; Goertz-Allmann et al. 2014; Verdon et al. 2015). Previous studies indicate that massive fluid injection can trigger induced seismicity (e.g. Ellsworth 2013; Bao & Eaton 2016). The magnitude of an induced earthquake was estimated, in Oklahoma, to be as large as Mₐ 5.7 (Karanen et al. 2013). It is not clear if CO₂ injection and associated migration could induce larger microseismic events (G50; G42; Gan & Frohlich 2013).

The Aneth CO₂-enhanced oil recovery (EOR) field was a CO₂-EOR pilot site for the Phase II of the Southwest Regional Partnership...
on Carbon Sequestration project supported by the U.S. Department of Energy. The field is located at the Paradox Basin of the southeastern Utah (Fig. 1a). From August 2007 to September 2009, a total of 254,000 metric tons of CO₂ were injected into the oil reservoir (Fig. 1b). Thousands of microseismic events were detected using a single-borehole geophone array (Zhou et al. 2010; Soma & Rutledge 2013). The vertical borehole cemented-in geophone array contains 16 levels of three-component geophones and 7 levels of vertical-component geophones, ranging in depth below surface between 808 and 1707 m. Between 25 April 2008 and 16 March 2009, about 3800 microseismic events with moment magnitudes from −1.2 to 0.8 were detected using the vertical borehole geophone array, and 1266 microseismic events were relocated with a high depth-resolution using both direct and reflected phases (Soma & Rutledge 2013). More than 95 per cent of the events are in the south cluster, while the remaining 5 per cent are in the north cluster. The observed events are located within two microseismically active regions, a northerly and southerly cluster (Fig. 1b). Hypocentres of these microseismic events (Fig. 1c) were further refined using a double-difference fat-ray method (Chen et al. 2014a). Azimuths to microseismic events were determined from the horizontal components of P-wave particle-motion trajectories (Eaton 2018). The particle-motion data from the cemented-in geophone array were highly linear and consistent among receiver levels. The relative azimuth errors of the microseismic events in the south cluster were smaller than 0.5° (Rutledge & Soma 2010; Soma & Rutledge 2013). Microseismic event locations at the Aneth CO₂-EOR field provide two important constraints: (1) the microseismicity of the south cluster occurs beneath the reservoir; and (2) the microseismicity distributes along the SW–NE stripes (Soma & Rutledge 2013; Chen et al. 2014a). Moment-tensor inversion can help characterize these microseismic events, addressing questions such as: (1) Are the fault planes consistent with the geographic distribution of the microseismicity? (2) Do the microseismic events occur in newly created or pre-existing faults/fractures? (3) Does the CO₂ injection/migration induce the microseismicity? (4) Are there potential risks for the long-term storage?

To address the aforementioned scientific questions, it is necessary to develop a new method to invert the moment tensors using a single-borehole array. Previous studies revealed the presence of microseismic event clusters (multiplets) which produce similar waveforms at all observation stations. The multiplets in a cluster occur along a plane with similar focal mechanisms, which can be interpreted as in a fault/ fracture or asperity (Augliera et al. 1995; Phillips et al. 1997; Tezuka & Niitsuma 2000). The variation of focal mechanisms is reported less than 5° (Dahm et al. 1999). Recently, Shelly et al. (2016) developed a new strategy for earthquake focal mechanism using waveform-correlation-derived relative polarities and cluster analysis. The strategy was to cluster events with similar patterns of polarities and to apply focal-mechanism inversion to the grouped polarity data. Vavrycuk (2015) inverted for a composite moment tensor using joint inversion of multiple earthquake data recorded by surface seismic stations. Grechka et al. (2016) estimated the moment tensor of a microseismic event in vertical transversely isotropic medium using a single-well receiver array, based on an assumption that the microseismic event has a tensile moment tensor.

We develop a new adaptive moment-tensor joint inversion method for single-borehole geophone array. Our method clusters events with similar waveform similarities and radiation patterns. We invert clustered events through minimizing waveform misfits between data and synthetics, rather than polarities. We then invert a moment tensor for each event with a limited searching range based on the joint inversion result.

We present the adaptive moment-tensor joint inversion method in Section 2. We verify the improved inversion accuracy of our inversion method using six sets of synthetic tests with one geophone array within a borehole in Section 3. We apply our adaptive joint inversion method to microseismic data acquired using a single borehole geophone array at the CO₂-EOR field at Aneth, Utah in Section 4. The results demonstrate that our joint inversion method is capable of reducing inversion uncertainty caused by a limited azimuthal coverage of geophones. We discuss the geological implications in Section 5. Our inverted focal mechanisms of microseismic events are consistent with the event spatial distribution in subparallel pre-existing fractures.

2 ADAPTIVE MOMENT-TENSOR JOINT INVERSION OF CLUSTERED MICROSEISMIC EVENTS

A moment tensor (\(M\)) is a mathematical representation of the displacement field of a seismic source, consisting of nine couples \(M_{ij}\) (i = 1, 2, 3, j = 1, 2, 3). The elements of \(M_{ij}\) for the geographic reference frame are \(M_{ij} = S \epsilon_{ijk}\), where \(\epsilon_{ijk}\) is the stiffness tensor, \(S\) is the rupture area, \(\epsilon_{1}\) is the component of the slip vector and \(\epsilon_{2}\) is the component of the fault normal. Since the moment tensor is symmetric, the number of independent moment-tensor elements reduces from nine to six in any coordinate systems. The scalar seismic moment (\(M0\)) is equal to \(\sqrt{\frac{2}{3}} \sum M_{ij}^2\) (Grechka et al. 2016; Eaton 2018).

The moment tensor can be decomposed into three components: the double-couple (DC), isotropic (ISO) and compensated linear vector dipole (CLVD) components. Quantities \(M_{ij}\) (i = 1, 2, 3) are the eigenvalues of moment tensor. For \(|M_1| \geq |M_2| \geq |M_3|\), we compute \(\varepsilon = -M_{min}/M_1\), \(M_{min}\) is the minimum value of \(M_i\), then we have

\[
\begin{bmatrix}
M_1 & 0 & 0 \\
0 & M_2 & 0 \\
0 & 0 & M_3
\end{bmatrix} = \frac{1}{r} \epsilon \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} \left(1 - 2 \epsilon M_0\right) + \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} + \begin{bmatrix}
-1 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} , \text{when } \epsilon > 0
\]

\[
M_{CLVD}^{CDF} = \epsilon M_1
\]

\[
M_{CLVD}^{CDF} = \epsilon M_3
\]

ISO is equal to \(\frac{2}{3} \frac{\sqrt{\pi}}{\sqrt{2}} M_0 \times 100\text{ per cent}\), and its value is from −100 per cent (implosion) to 100 per cent (explosion). CLVD is defined as \(2\pi r \times (100\text{ per cent} - \text{ISO})\), where the value of CLVD is between −100 per cent (tensile) and 100 per cent (compression). The P- or T-axes of the CLVD are consistent with those of the DC component (Zhang et al. 2016; Eaton 2018). The DC component represents shear motion on a fault with strike, dip and rake angles. The ISO component describes volumetric strain and represents the same source motion in all directions, such as explosive or implosive sources. The CLVD component corresponds to volume-preserving dipole motion where strain along one axis is compensated by contraction or expansion along the other axes (Julian et al. 1998). The focal mechanism is the physical representation of the moment tensor, including shear, ISO and CLVD components. The moment tensor consists of the strike, dip, rake, ISO, CLVD and seismic moment (Aki & Richards 2002). It describes the focal mechanism and the moment magnitude. Each event is represented by seven parameters: strike, dip, rake, ISO, CLVD, moment and source duration...
We develop a moment-tensor joint inversion method to reduce inversion uncertainty, particularly for data acquired using a single-borehole geophone array. The basic principle is that if there are one vertical-borehole geophone array and several microseismic events with the same or very similar focal mechanisms (Fig. 2a), reciprocally, it is equivalent to the source–receiver distribution of one microseismic event and several vertical-borehole arrays (Fig. 2b). In other words, if we jointly invert the three events together using a focal mechanism, we increase the azimuthal coverage of the microseismic event. If the focal mechanisms vary slightly, the inversion would obtain the average focal mechanism for all the events. Another advantage of the joint inversion is to reduce the inversion uncertainty, through inverting a large amount of microseismic data simultaneously.

Our method is illustrated using the flow chart in Fig. 3. We first apply a bandpass filter to microseismic data to obtain data in the frequency band of 10–50 Hz, because the frequency range of the data spectra is from 10 to 100 Hz, with strong noise in the frequency band between 60 and 70 Hz. We discard the data with signal-to-noise ratio (SNR) less than 2. SNR is defined as the ratio of maximum absolute amplitude of signal (–0.05 to 0.15 s) to the maximum absolute amplitude of noise (–0.25 to –0.05 s), where time zero is the predicted arrival time. The method classifies microseismic events into clusters based on similarities in microseismic waveforms and radiation patterns. We adopt 90 per cent as a threshold of the full-waveform correlation coefficient, ensuring that microseismic events are
Data processing

Discard seismic data with SNR < 2

Cluster microseismic events based on waveform and radiation pattern similarities

Compute Green’s functions for all the events

Input data of microseismic data in Cluster N

Joint Inversion:
Invert for a focal mechanism for Cluster N

Adaptive Inversion:
Invert for a focal mechanism for each event around the joint inversion result

Output focal mechanism for Cluster N

Yes

More clusters?

No

Output focal mechanisms for all clusters

Figure 2. The reciprocal principle of the moment-tensor joint inversion. (a) Top view of a vertical borehole array (triangle) and three microseismic events (beach balls) with the same focal mechanism. (b) Top view of three borehole arrays (triangles) and a microseismic event (beach ball) reciprocal to (a).

Figure 3. Flow chart of the adaptive moment-tensor joint inversion method.

located in adjacent to one other and their waveforms are comparable to one another. We then extract maximum amplitudes from a time window for all the channels in a geophone array, to form an amplitude array. We calculate correlation coefficients for the amplitude arrays. Similar focal mechanisms would produce similar seismic waveforms and radiation patterns for all the phases including P and S waves and their coda waves at the receivers, which include the effects of a source radiation pattern and wave propagation effects. Since the clustered events are adjacent to one another, the wave propagation effects can be ignored. High correlation coefficients of full waveforms and maximum waveform amplitudes for all the geophones ensure similar focal mechanisms/radiation patterns for a given cluster of events. We select a correlation coefficient threshold to ensure the similarity of focal mechanism and verify the robustness of the joint inversion method. We examine the relationship between correlation coefficients of radiation patterns and focal-mechanism parameters (Fig. S1). A correlation coefficient of higher than 90 per cent corresponds approximately to a DC focal-mechanism variation less than ±15°, an ISO variation less than ±15 per cent or a CLVD variations less than ±20 per cent using the Aneth source–receiver configuration in Fig. 1(b), the seismic velocity model in Fig. 1(d) and a target focal mechanism of 230°/50°/0°/0 per cent/~40 per cent (strike/dip/rake/ISO/CLVD). We find that the correlation coefficient can change significantly because of polarity change. However, we also note that constraining moment tensors strongly depends on the station distribution (Nayak & Dreger 2018). We plot the correlation coefficients of radiation patterns and focal-mechanism parameters using a focal mechanism of 185°/45°/270°/40 per cent/40 per cent (Fig. S2). A correlation coefficient of higher than 90 per cent corresponds approximately to a strike variation of less than ±20°, a dip variation of less than ±12°, a rake variation of less than ±20°, an ISO variation of less than ±50 per cent or a CLVD variation of less than ±50 per cent. In Fig. S2, the radiation pattern is not sensitive to non-DC components. Therefore, the relationship between focal mechanisms and station distributions should be carefully examined. The method might fail when the phases or amplitudes of waveforms change slowly in recording regions of the focal sphere, mostly for moment tensors with non-DC components.

We compute Green’s functions using a frequency–wavenumber method (Zhu & Rivera 2002). We use the isotropic velocity models shown in Fig. 1(d). The density is equal to Vp = 0.32 + 0.77 (Gardner et al. 1974). Qp and Qs are 1000 and 500, respectively (Dziewonski & Anderson 1981). The Green’s functions are generated for every epicentral distance and every source depth with an interval of 0.01 km, and for every geophone depth for the borehole array. Each microseismic event is represented by seven parameters: strike, dip, rake, ISO and CLVD for focal mechanism, and the source duration and moment. Therefore, synthetics are the results of Green’s functions convolved with source–time functions. We invert for a uniform focal mechanism (strike/dip/rake/ISO/CLVD) for a cluster of events, while each event has its source duration and moment. A total of 5 + 2 = N parameters are involved in the inversion with N being the number of events in the inversion.

The objective function is \( \sum_{j=1}^{N} \sum_{n=1}^{J} \left| d_{n}^{j} - s_{n}^{j} \right| / A_{n}^{j} \), where \( j \) is the channel number and \( n \) is the event number, \( d_{n}^{j} \) is a seismic trace and \( s_{n}^{j} \) is the synthetic trace. \( A_{n}^{j} \) is the maximum absolute amplitude of \( d_{n}^{j} \). The misfit of each channel of data is normalized to the maximum absolute amplitude of the data. All seismic traces are equally weighed in the inversion. The time window used for the data and synthetics is from –0.05 to 0.15 s. Time 0 s is a predicted-phase arrival time calculated based on the 1-D velocity model (Fig. 1d). Because inaccurate velocity models may lead to mismatches between observed data and synthetics, such mismatches may lead to wrong inversion results. We allow observed data to shift within 0.02 s to reach higher correlation coefficients, and then calculate the objective function. To avoid cycle skipping effect (mismatch of different seismic phases), we allow the data to shift 0.02 s only, smaller than seismic duratins of those events. The inversion searches the best values of the seven parameters to minimize P and S data misfits using a simulated heat-annealing algorithm (Chen et al. 2014b). Because the seven parameters for each event are coupled among them when seismic receiver coverage is not perfect, the simulated-heat-annealing method based on a non-linear global search would perform better than a linear inversion. One focal mechanism can be described using two fault planes plus non-DC components that would generate identical seismic waveforms. We only need to search a half parameter space for a strike of 0°–360°, dip of 0°–90° and rake of –90° to 90° (Zhao & Helmberger 1994; Li et al. 2011) and for the ranges of the ISO and CLVD components –100 to 100 per cent and –100 to 100 per cent, respectively. To fit the P waveforms...
in the vertical and radial components and S waveforms in the transverse components, we need a correct source time function (source duration and moment). The search space for the source duration is between 0.02 and 0.1 s, corresponding to the frequency band of 10–50 Hz, and that for the moment is between $10^6$ and $10^{12}$ N·m. Because we use a limited frequency band for the seismic data, the moment and source duration may not be accurate, and we focus on resolving focal mechanisms in this study.

We further invert a moment tensor for each event in a limited range around the joint inversion result. The searching ranges for the moment and source duration may not be accurate, and we focus on resolving focal mechanisms in this study.

We conduct the second synthetic test for 50 microseismic events with different focal mechanisms to verify the capability of our adaptive joint inversion method to reduce the inversion error using a single-borehole geophone array. Focal mechanisms of clustered microseismic events vary usually less than 5° in strike, dip, and rake angles (Dahm et al. 1999). We examine the correlation coefficient of radiation patterns using the Aneth source–receiver configuration in Fig. 1(b), the seismic velocity model in Fig. 1(d) and a target focal mechanism of $230°/50°/0°$ per cent/–40 per cent (strike/dip/rake/ISO/CLVD). A correlation coefficient of higher than 90 per cent corresponds approximately to a DC focal-mechanism variation of less than $8°$, an ISO or CLVD variation of less than 15 per cent. In this synthetic test, the focal parameters are randomly distributed within the variation ranges for the 50 events. The other configurations are the same as those in the first synthetic data test.

We perform joint inversion and compare the results with those obtained using individual/independent inversion for each event. The individual inversion searches a focal mechanism for each event independently, while the joint inversion assumes a uniform focal mechanism for all the clustered events. The normalized data misfits are displayed in Fig. 4(a). As the figure shows, the joint inversion (red thick curve) has a better convergent rate and reach a smaller data misfit at the 1000th iteration. The individual inversion for some events may give a reasonable result (blue thin curves), while that for other events may yield incorrect results because of converging to local minima (blue thin curves). However, the individual inversion (blue thick curve) is not able to converge as well as the joint inversion (red thick curve). We also define a model misfit as $\frac{|\Delta$ strike$/360°| + |\Delta$ dip$/90°| + |\Delta$rake$/360°| + |\Delta$ISO$/2| + |\Delta$CLVD$/2|}{5}$. As aforementioned, we do not study seismic moment and source duration in this research. The joint inversion can achieve a model misfit of 0.002, which is only 2.2 per cent of 0.09 of the model misfit for the individual inversion (Fig. 4b).

3 SYNTHETIC TESTS OF THE ADAPTIVE MOMENT-TENSOR JOINT INVERSION

We perform six resolution tests in the section, to verify the robustness of our adaptive moment-tensor joint inversion method using noise-free data, noisy data, inaccurate velocity models and inaccurate event hypocentre locations.

The first synthetic test is to evaluate the resolution of the joint inversion method for a group of 50 events with the same focal mechanism. The source and receiver configuration is similar to that used for monitoring CO$_2$ injection at the Aneth oil field (Fig. 1b). There is a vertical borehole geophone array with 16 levels of 3C geophones and 7 levels of 1C geophones in the depths between 808 and 1707 m. The azimuthal range is between $285°$ and $289°$ with 1° intervals; the distance range between 1.5 and 1.54 km with 0.01 km interval; and the depths of 1.91 and 1.92 km. We use a small focal coverage to verify our inversion method. The method is valid for larger ranges in hypodistances, depth and azimuth coverages. The source parameters consist of a strike of $230°$, a dip of $50°$, a rake of $0°$, an ISO of 0, a CLVD of $–40$ per cent, a random seismic duration between 0.02 and 0.1 s and a random seismic moment between $1.7 \times 10^{10}$ and $1.7 \times 10^{11}$ N·m. We generate synthetic data using the above source parameters and a velocity model as shown in Fig. 1(d).

We carry out joint inversion of synthetic data for the 50 microseismic events, and compare the results with those obtained using individual/independent inversion for each event. The individual inversion searches a focal mechanism for each event independently, while the joint inversion assumes a uniform focal mechanism for all the clustered events. The normalized data misfits are displayed in Fig. 4(a). As the figure shows, the joint inversion (red thick curve) has a better convergent rate and reach a smaller data misfit at the 1000th iteration. The individual inversion for some events may give a reasonable result (blue thin curves), while that for other events may yield incorrect results because of converging to local minima (blue thin curves). However, the individual inversion (blue thick curve) is not able to converge as well as the joint inversion (red thick curve). We also define a model misfit as $\frac{|\Delta$ strike$/360°| + |\Delta$ dip$/90°| + |\Delta$rake$/360°| + |\Delta$ISO$/2| + |\Delta$CLVD$/2|}{5}$. As aforementioned, we do not study seismic moment and source duration in this research. The joint inversion can achieve a model misfit of 0.002, which is only 2.2 per cent of 0.09 of the model misfit for the individual inversion (Fig. 4b).

The third synthetic test is to manifest the robustness of the adaptive joint inversion using noisy data. Seismic noise would increase the inversion errors, particularly when the geophone azimuthal coverage is poor. One or two poor-quality waveforms would lead to biased inversion results. In this synthetic test, we add seismic noise extracted from real data recorded at the Aneth CO$_2$-EOR field to synthetic data used in the second synthetic test. We conduct adaptive joint inversion and individual inversion of synthetic data with different noise levels, ranging from 10 to 100 per cent of the maximum amplitude of each channel data. Although it is not a real case
that amplitudes of seismic noise are percentages of those of seismic data, percentage of maximum amplitude is an effective approach for comparison. We run 50 inversions for each noise level using different initial focal mechanisms (uniform random distribution in the searching space) and obtain the inversion error (standard deviation error) for each parameter. The inversion errors of the strike, dip and rake are below 6° when the noise level is lower than 60 per cent (Fig. 6a), and those of ISO and CLVD are smaller than 11 and 10 per cent when the noise is lower than 50 per cent (Fig. 6b). This numerical test demonstrates that our adaptive joint inversion method is robust when the noise percentage is as high as 50 per cent. We also test a case with the real noise from recorded data and synthetic waveforms generated by an $M_0$ 0 event. SNRs of the most waveforms are higher than 5. The inversion errors of the DC components are smaller than 5°, and those of ISO and CLVD are less than 10°. Joint inversion of multiple event data can statistically reduce the influence of the noise on inversion.

The fourth synthetic test is to study the inversion error of the adaptive joint inversion versus the distance between geophones and microseismic events. The accuracy of focal mechanism inversion depends on the coverage of the focal sphere (e.g. Pesicek et al. 2016). The angular coverage range of ray take-off angles of microseismic waves to the bottom and top geophones in a single vertical borehole array becomes smaller with increasing the distance. We use six clusters of microseismic events located at distances of 1.4–1.44 km, 1.5–1.54 km, 1.6–1.64 km, 1.7–1.74 km, 1.8–1.84 km and 1.9–1.94 km, respectively. The distances correspond to the angular coverages of approximately 26°, 25°, 24°, 23°, 22° and 21°, respectively. These clustered event locations are similar to those occurred during CO2 injection at the Aneth CO2-EOR field. We carry out 50 inversions for each cluster of microseismic events using different initial focal mechanisms. The inversion errors of the double-couple components are smaller than 4° for all clustered events (Fig. 7), and the inversion errors of the ISO and CLVD components are less than 12 and 18 per cent, respectively. Therefore, the inversion errors of the focal mechanism parameters obtained using our adaptive joint inversion method are not biased in the distance range of microseismic events occurred during CO2 injection at the Aneth CO2-EOR field.

The fifth synthetic test is to study the inversion error caused by the hypocentre mislocation. Soma & Rutledge (2013) suggested that the event hypocentre uncertainty is in average of 11 m. Therefore, we invert for focal mechanisms of 50 microseismic events with perturbations of both their distances from the monitoring well and their depths up to 20 m. The perturbations of their azimuths relative to the monitoring well are up to 5°. The inversion errors of the double-couple components are less than 6°. The inversion errors are 11 per cent for ISO components and 10 per cent for CLVD components, respectively. Such inversion errors would not bias our moment-tensor inversion results.

The final synthetic test is to evaluate the influence of an inaccurate velocity model on our moment-tensor inversion results, particularly on the non-DC component. Previous studies indicate that inaccurate seismic velocity models and hypocentre mislocation may result in inaccurate non-DC components (e.g. Sileny 2009). The geological model, constrained by 3-D reflection seismic data and wireline well logs, demonstrated that the seismic velocity structure at the Aneth CO2-EOR field is related to stratigraphy. The exposed bedrock geology shows that the strata of the Jurassic Recapture Shale Member of the Morrison Formation through the Cretaceous Dakota Sandstone dip less than 5° to the northeast (Soma & Rutledge 2013). Therefore, the thickness of each layer is fairly accurate, because it is constrained using well logs. Our velocity model is built using a sonic log (Soma & Rutledge 2013). However, the P-wave velocity model built based on the sonic log represents velocities in the high frequency, usually in the order of 10 kHz. The velocities in high frequency are not identical to that in the low frequency because of dispersion. Our S-wave velocity model is derived from the P-wave velocity model using a constant velocity ratio of 1.7.

We perform the adaptive joint inversion for 50 microseismic events using the same source and receiver configurations as the second synthetic test, but using Green’s functions computed with inaccurate velocity models. The inaccurate velocity models employ the same thickness for each layer as the true model, with ±1 to ±6 per cent perturbations of velocity values in the layers. The errors of the inversion results of focal-mechanism parameters are shown in Fig. 8. The inversion errors are less than 20 per cent for CLVD and ISO, less than 7° for the strike, dip, and rake, when the velocity perturbation is within 3 per cent. The dip inversion error increases more rapidly with increasing velocity perturbation than the other parameters, suggesting that an inaccurate velocity model would lead to an unreliable inversion result of the dip angle. We use histograms (Fig. S3) to exhibit the inversion differences between the inverted parameters and the true parameters. We note that the inaccurate velocity models would systematically bias the inversion result.
We compare the waveforms and radiation patterns of microseismic events among one another, and cluster 717 events into seven clusters based on the waveform and radiation pattern similarities. We display an example of waveform similarity (Fig. 9b) for microseismic events in Cluster C1 (red beach balls in Fig. 9a), acquired using the geophone at the top of the receiver array. Similar seismic radiation patterns correspond to similar focal mechanisms. As aforementioned, we extract maximum amplitudes from 5.5-s data windows of all channels in the geophone array. We calculate correlation coefficients for the amplitude arrays. We plot the radiation patterns for all the events in Cluster C1 in Fig. 9(c). The figure indicates the high similarity of radiation patterns among those events. We exhibit the absolute amplitude ratio between SH-waves of transverse components and \( P \) waves of vertical components in Fig. S4.
The variation indicates the azimuthal coverage of the focal sphere using our method. We also show the typical radiation patterns for all the clusters in Fig. 9(d). The above waveform and radiation pattern analyses confirm our assumption that microseismic events in a cluster have similar focal mechanisms. We also plot the waveforms and their absolute amplitude ratios between SH waves of transverse components and P-waves of vertical components for an example event in Fig. S5, to show the waveform variation of an event. The remaining approximately 500 events (black circles in Fig. 9a) are not well correlated with the 717 events and not included in further analysis. We then apply individual inversions and our new adaptive joint inversion methods to the 717 events in the following two subsections, respectively.

### 4.1 Individual moment-tensor inversion of each microseismic event

We first conduct individual inversion of the 717 events, and present the results of the full six-component moment tensor in Fig. 10(a). The results contain both pure implosive and explosive sources...
within each cluster. However, pure implosive and explosive sources have not been observed for microseismic mechanisms. Previous studies suggested that microseismic waveforms exhibit strong double-couple components, indicating shear motion on fractures (e.g. Maxwell 2014). The inversion results of pure implosion and explosion indicate that those inversion results are not reasonable because of convergence to local minima.

Vavrycuk (2007) demonstrated that the double-couple focal mechanism can be constrained using a vertical-borehole geophone array. Rather than inverting all six components, we invert the data for the double-couple component only using individual inversion and obtain the inversion results in Fig. 10(b) with strike-slip faulting in red, normal faulting in green and thrust faulting in blue. Fig. 10(b) shows that there are approximately 400 events with strike-slip faulting and roughly 300 events with normal faulting and thrust faulting. The co-existence of the normal faulting and thrust faulting is usually unreasonable, as these two types of faulting should not occur at the same location. The normal faulting represents a horizontal extension motion, while the thrust faulting represents a horizontal compression motion. These unreliable inversion results may be due to the weak amplitudes of (consequently low SNR) the P-wave data recorded with the four geophones at the bottom of the monitoring well. The individual inversion may converge to local minima.

4.2 Adaptive moment-tensor joint inversion of clustered microseismic events

We then conduct adaptive joint inversion of microseismic data for the seven clusters of the selected 717 events. The adaptive joint inversion consists of two steps: joint inversion of events in each cluster using the same focal mechanism, and adaptive inversion of each event’s focal mechanism based on the joint inversion result. The joint inversion results are displayed in Table 1 and Fig. 11. The seven clusters are mostly aligned in stripes (colour-coded dots in Fig. 11). The microseismic events are mostly dominated by a strike-slip faulting with strike angles of 219°–229°, dip angles of 50°–60°, rake angles of –13° to 19°, ISO components of –2 to 8 per cent, and CLVD components of –42 to 18 per cent for all seven clusters.

We further invert the microseismic data for each event’s focal mechanism using the adaptive inversion. The searching ranges for the adaptive joint inversion are ±15° from the inverted strike, dip and rake, ±15 per cent from the inverted ISO, ±20 per cent from the inverted CLVD and ±20 per cent from the seismic duration and moment of the joint inversion results. The results are displayed in Figs 12 and 13. Fig. 12(a) shows consistent but slightly varying focal mechanisms, rather than co-existence of implosion and explosion in Fig. 10(a), and normal faulting and thrust faulting in adjacent areas in Fig. 10(b). Fig. 12(b) indicates that our adaptive moment-tensor joint inversion method gives a smaller data misfit (red curve) than that of the individual inversion of full moment tensors (green curve) and double-couple component (blue curve). We present waveform fittings of five microseismic events in each cluster in Figs S7–S41. The synthetics (red traces) match the microseismic waveforms (black traces in Figs S7–S41) reasonably well. The adaptive inversion results exhibit slightly varying focal mechanisms. Focal mechanisms of the 717 microseismic events are within strikes of 215°–235°, dips of 45°–65°, rakes of –20° to 25°, ISOs of –4 to 12 per cent and CLVDs of –50 to –10 per cent. The inversion results of focal mechanisms shown in Fig. 13 exhibit subclusters. In particular, the events in Cluster 4 are divided into two subclusters highlighted by the red ellipses in Fig. 13. The shallower events to the southwest have strikes of 227°–232° (Fig. 13a) and dips of 50°–55° (Fig. 13c), while those deeper events to the northeast have strikes of 222°–227° (Fig. 13b) and dips of 45°–50° (Fig. 13d). We display the radiation patterns for the events in the two subclusters in Fig. S6(a) and their stacked radiation patterns in Fig. S6(b). Fig. S6(c) exhibits the amplitude distributions for the events in the two subclusters recorded by the channel 27 in Fig. S6(a). The figure indicates slightly different radiation patterns between these two subclusters. The other six clusters also exhibit subcluster patterns with larger variations in focal mechanism than Cluster 4. The
Table 1. Focal mechanisms of seven clusters of the Aneth microseismic events obtained using the joint inversion.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Events</th>
<th>Fault plane 1</th>
<th>Fault plane 2</th>
<th>ISO per cent</th>
<th>CLVD per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strike</td>
<td>Dip</td>
<td>Rake</td>
<td>Strike</td>
<td>Dip</td>
</tr>
<tr>
<td>C1</td>
<td>134</td>
<td>227</td>
<td>52</td>
<td>16</td>
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<tr>
<td>C2</td>
<td>20</td>
<td>229</td>
<td>52</td>
<td>17</td>
<td>129</td>
</tr>
<tr>
<td>C3</td>
<td>123</td>
<td>228</td>
<td>51</td>
<td>19</td>
<td>126</td>
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<td>159</td>
<td>228</td>
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<td>18</td>
<td>127</td>
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<td>C5</td>
<td>132</td>
<td>222</td>
<td>60</td>
<td>5</td>
<td>129</td>
</tr>
<tr>
<td>C6</td>
<td>96</td>
<td>225</td>
<td>55</td>
<td>8</td>
<td>130</td>
</tr>
<tr>
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<td>53</td>
<td>219</td>
<td>50</td>
<td>−13</td>
<td>318</td>
</tr>
</tbody>
</table>

Figure 11. Distributions (colour-coded dots) and focal mechanisms (colour-coded beach balls) of the microseismic events in the seven clusters for (a) map view and (b) depth view along AA’–BB’. The beach balls and the numbers below it represent the focal mechanism for each cluster. The figure shows the Aneth microseismic event distribution and focal mechanisms.

There are three advantages of our adaptive joint inversion method compared with the individual inversion. First, our adaptive joint inversion method is capable of inverting the moment tensor reliably using a single vertical-borehole geophone array, but the individual inversion results in a large inversion uncertainty. Fig. 12 shows that our adaptive inversion produces consistent and reasonable results. Greczka et al. (2016) inverted for moment tensors by simultaneously constraining a particular component. The method assumed that the event occurs in tensile cracks. Our method inverts for the full moment tensor based on the assumption that there are multiple events with similar focal mechanisms in different azimuths. Secondly, our adaptive joint inversion uses microseismic data of multiple events to reduce the inversion uncertainty statistically, particularly for microseismic data with strong noise. Thirdly, our inversion is semi-automated. We only need to classify the events into clusters and invert the focal mechanisms for the clustered events. Individual inversions are not robust to yield a correct inversion result for each event. Examination of numerous individual inversion results is very time-consuming. Our adaptive joint inversion method jointly inverts a large number of microseismic events for focal mechanisms simultaneously, and adaptively inverts the focal mechanism of each event within a limited range around the joint inversion results to alleviate the local minimum problem. Although incorporating time shifts between the data and synthetics might increase the inversion uncertainty, it makes the inversion process automated.

5 DISCUSSION

5.1 Subparallel pre-existing fractures

The high-precision location of the microseismic events at the Aneth CO2-EOR field shows that they occurred along subparallel stripes, which may indicate subparallel fracture zones (Soma & Rutledge 2013; Chen et al. 2014a). In this study, we further demonstrate that focal mechanisms of these microseismic events are consistent with their spatial distribution (Fig. 14). We plot ten dashed lines along the strike angles of the focal mechanisms for the seven clusters. The strikes of the focal mechanisms (dashed lines in Fig. 14) are consistent with the striped distributions of the microseismic events (colour-coded dots in Fig. 14). Therefore, we suggest that these events occurred along the subparallel fracture zones with slightly varying focal mechanisms. The subparallel fractures may infer bookshelf faulting. Bookshelf faulting consists of a series of parallel faults and a narrow band of strike-slip earthquakes produced by shear rotation (Tappornier et al. 1990; Wetzel et al. 1993). On the other hand, the depth range of each cluster is only 10–20 m. The depth resolution is not capable of resolving the dip angle of the hypocentral distribution for each cluster.

The subparallel fracture geometry and microseismic focal mechanisms are also consistent with fault-like gouges or observed geological imperfections at the Aneth field. Cluster 4 may indicate two groups of geological imperfections with slightly different geometries. The surface geological survey indicated that no large displacement, laterally extensive faults were found in the Aneth Unit. Nevertheless, small-localized normal faults and deformation bands were identified (Morgan et al. 2010). Deformation bands are fault-like fractures with typically a few millimetres in width, but can be as long as several metres to tens of metres. They often accommodate displacement on the scale of millimetres to centimetres and occur as single bands or in clusters. Large clusters of deformation bands can usually be linked to the occurrence of large offset faults, though each band within the cluster does not necessarily represent a slip-surface (Fossen & Bale 2007; Fossen et al. 2007; Morgan et al. 2010).
Figure 12. (a) Focal mechanisms inverted using the adaptive moment-tensor joint inversion method. The colour-code beach balls are the results of joint inversion (Fig. 11) for reference. (b) Comparison among normalized data misfits for the individual inversion of full moment tensors (green curve), the individual inversion of double-couple component (blue trace) and our adaptive moment-tensor inversion (red). The figure manifests the improved accuracy and spatial consistency of the adaptive joint inversion of microseismic data.

Figure 13. Strike angles (a, b) and dip angles (c, d) of the clustered microseismic events for (a, c) map view and (b, d) depth view along AA’-BB’. The colours represent different focal mechanisms. The figure displays the microseismic event distribution and focal mechanisms inverted using the adaptive joint inversion.

small localized fractures and deformation bands dip approximately 60° (Figs 2–3 and 2–4 in Morgan et al. 2010), consistent with our inversion results. The deformation bands in the Aneth unit exhibit both SE–NW and SW–NE trends (fig 2–5 in Morgan et al. 2010), and SW–NE trend is consistent with the inverted strikes of the focal mechanisms. The microseismic events localized in two area: north and south clusters (Fig. 1b), which might indicate the localization of those pre-existing weak zones. The magnitudes of those microseismic events are between −1.2 and 0.8. The event magnitude might be limited by the size of the pre-existing weak zones. Although the observed geological features do not necessarily correspond to the geometry of deep fractures, they form in response to the tectonic stress that cause localized strain in this area. Therefore, it is reasonable to use them to infer the characteristics of deep subsurface fractures.

The focal mechanisms are dominated by strike-slip motions with the rakes between −13° and 19°. The strike-slip focal mechanisms of our inversion result are consistent with previous observations of reactivated faulting (e.g. McNamara et al. 2015; Bao & Eaton 2016). The events are more likely controlled by the tectonic stress and the fracture geometry. The strike-slip focal mechanisms could
be driven by a west/northwest directed compression as suggested in a previous study (Zoback & Zoback 1980).

5.2 Possible existence of large CLVD components

Our inversion results show that ISO components are between −4 and 12 per cent and CLVD components range from −50 to −10 per cent for all the clusters (Fig. 15). Our synthetic tests indicate that the ISO inversion uncertainty is usually larger than 10 per cent (Figs 6b, 7b and 8b), and thus we cannot conclude the existence of the ISO components in this study.

An uncertainty of the inversion result is that non-DC components may be affected by hypocentre mislocation and inaccurate seismic velocity models (Sileny 2009). In our synthetic tests, we demonstrate that our inversion is robust when the hypocentre uncertainty is less than 20 m and the inaccurate velocity with perturbation within 3 per cent. Previous studies suggested that fluid-induced crack opening or closing could generate the non-DC components. Zhang et al. (2016) indicated that many other factors can also cause CLVD, such as seismic noise, complexity of fractures, and the rupture of parallel fractures at the similar time and close distance. Our synthetic test shows that our CLVD inversion results are reliable until seismic noise is larger than 80 per cent. Therefore, the large values of the CLVD components might indicate crack opening by CO2/wastewater injection or rupture complexity.

6 CONCLUSIONS

We have developed a novel adaptive moment-tensor joint inversion method. The method consists of two steps: first jointly invert clustered microseismic events with similar waveforms and radiation patterns for a reference focal mechanism, and then adaptively inverts for focal mechanism for each microseismic event within a searching range around the joint inversion result. We have verified the robustness of our new method using six synthetic datasets. The first test proved that the joint inversion method could obtain a more accurate result than the individual inversion. The second test indicated that, even though the focal mechanism of clustered microseismic events can have variations of focal-mechanism parameters, the joint inversion method has a better convergent rate and yields an average focal mechanism reliably, but the individual inversion often converges to local minima. Our adaptive inversion further improves the inversion result for each event. The third synthetic test demonstrated that our new inversion method is robust when the noise level is lower than 50 per cent of the signal level. The fourth synthetic test confirmed that the inversion error of our new method increase slightly with the distance. The fifth synthetic test proved that microseismic event mislocation does not bias our inversion results. The sixth synthetic test demonstrated the robustness of our method in inaccurate velocity models.

We have applied our adaptive joint inversion method to 717 microseismic events at the Aneth CO2-EOR field, and compared the results with those obtained using individual inversion. The inversion results contain large uncertainty and unreasonable geologically. By contrast, our adaptive joint inversion produces consistent focal mechanisms for all events with strikes of 215°–235°, dips of 45°–65°, rakes of −20° to 25°, ISOs of −4 to 12 per cent and CLVDs of −50 to −10 per cent. These inverted focal mechanisms are consistent with the microseismic spatial distribution along stripes, the geological survey and the tectonic stress. Our results indicate that these microseismic events should have occurred in the pre-existing fractures or geological imperfections. The large values of the CLVD components might indicate crack opening by CO2/wastewater injection or rupture complexity.

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REFERENCES


**SUPPORTING INFORMATION**

Supplementary data are available at *GJI* online.

Fig. S1: Correlation coefficients of radiation patterns as functions of strike (a), dip (b), rake (c), ISO (d) and CLVD (e) centred on a focal mechanism of 230°/50°/0°/0/40 per cent. The dash lines indicate the correlation coefficients of 0.9.

Fig. S2: Correlation coefficients of radiation patterns as functions of strike (a), dip (b), rake (c), ISO (d) and CLVD (e) centred on a focal mechanism of 185°/45°/270°/40 per cent/40 per cent. The dash lines indicate the correlation coefficients of 0.9.

Fig. S3: Histograms of the inverted errors of the strike (a), dip (b), rake (c), ISO (d) and CLVD (e) during the synthetic test with random perturbation of ±3 per cent of velocity models.

Fig. S4: The absolute amplitudes between SH and P phases as a function of azimuth for a 3C geophone at the top of all the 3C geophones (black triangle in Fig. 1b).

Fig. S5: Seismic waveforms of a typical microseismic event in the vertical direction (a), the radial direction (b), and the transverse direction (c). All waveforms are normalized by the maximum amplitudes for comparison. (d) The absolute amplitudes between SH and P phases for 3C geophones from the bottom to the top.

Fig. S6: (a) Radiation patterns of microseismic events for the two subclusters in Cluster C4. The green traces represent radiation patterns of the microseismic events with strikes smaller than 228° (green and yellow dots in the highlighted red ellipse in Fig. 13a). The orange traces represent radiation patterns of the microseismic events with strikes greater than 228° (orange and red dots in the highlighted red ellipse in Fig 13a). (b) Stacked radiation patterns for the two subclusters in (a). Black arrows highlight the differences of the radiation patterns. (c) The histograms of normalized amplitudes for the two subclusters in (a).

Figure caption for Figs. S7–S41: Displacement waveform fitting between the P and S data (black traces), and the synthetics predicted by the inverted moment tensor (red dashed traces) for seismic events 2008163194759 in Cluster 1 (S1), 2008312122036 in Cluster 1 (S2), 2008319084540 in Cluster 1 (S3), 2008365165924 in Cluster 1 (S4), 2009025005850 in Cluster 1 (S5), 2008252143925 in Cluster 2 (S6), 2008260105512 in Cluster 2 (S7), 2008286120947 in Cluster 2 (S8), 2008326181420 in Cluster 2 (S9), 2009008212940 in Cluster 2 (S10), 2008160052703 in Cluster 3 (S11), 2008224035113 in Cluster 3 (S12), 2008316165131 in Cluster 3 (S13), 2008326102102 in Cluster 3 (S14), 2008264123610 in Cluster 3 (S15), 2008326123610 in Cluster 4 (S16), 2008324111345 in Cluster 4 (S17), 2008323121613 in Cluster 4 (S18), 2008335142749 in Cluster 4 (S19), 2008352094351 in Cluster 4 (S20), 2008164201212 in Cluster 5 (S21), 2008230110752 in Cluster 6 (S27), 2008296124838 in Cluster 6 (S28), 2009009185821 in Cluster 6 (S29), 2009023212451 in Cluster 6 (S30), 2008116131826 in Cluster 7 (S31), 2008230083527 in Cluster 7 (S32), 2008258084458 in Cluster 7 (S33), 2008357094721 in Cluster 7 (S34) and 2008366170337 in Cluster 7 (S35). Each channel labels with the receiver number and component to the left and the maximum amplitude on the top right. Z is the vertical P component, R is the radial P component and T is the transverse S component. The unit of the amplitude is 10–6 m.

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