

ARTICLE

Impact of source models on focal mechanism inversion in hydraulic fracturing distributed acoustic sensing monitoring

Quanlong He^{1,2*} , Shuaihong Liu³ , Tao Chen^{1,2} , Shaowei Sun^{1,2} , Yuqi Cheng^{1,2} , Guoquan Liu^{1,2} , Xiaodong Wang^{1,2} , and Zhao Han^{1,2} 

¹Logging Technology Research Institute, China National Logging Corporation, Xi'an, Shaanxi, China

²Well Logging Key Laboratory, China National Petroleum Corporation, Xi'an, Shaanxi, China

³Changqing Branch, China National Logging Corporation, Xi'an, Shaanxi, China

Abstract

Distributed acoustic sensing (DAS) has garnered growing attention for microseismic monitoring in hydraulic fracturing (HF) operations within unconventional oil and gas development. Conventional DAS sensors acquire single-component measurements along the optical fiber, which may introduce uncertainties in microseismic focal mechanism inversion—a critical step for HF performance assessment and reservoir stimulation optimization. This study evaluates the performance of double-couple (DC), general dislocation (GD), and moment tensor (MT) source models for microseismic focal mechanism inversion using downhole DAS data. We systematically investigated the effects of DAS array orientation, input focal mechanism, noise level, velocity uncertainty, and source location error on the inversion results. Our findings indicate that DAS-based focal mechanism inversion was strongly controlled by the horizontal source-receiver azimuthal coverage. For a horizontal-vertical DAS acquisition geometry, MT inversion exhibited sensitivity to dip-slip input mechanisms, 5% velocity errors, 10 m source location errors, and 40% noise levels, whereas DC and GD inversions remained comparatively robust. Given that HF-induced microseismic events may involve non-DC components, the GD model-based inversion represents a reliable approach for obtaining stable focal mechanisms in horizontal-vertical DAS monitoring configurations, thereby advancing the application of DAS technology in microseismic monitoring studies.

*Corresponding author:

Quanlong He
(hqlkmust@163.com)

Citation: He Q, Liu S, Chen T, *et al.* Impact of source models on focal mechanism inversion in hydraulic fracturing distributed acoustic sensing monitoring. *J Seismic Explor.*
doi: 10.36922/JSE026270120

Received: July 1, 2026

Revised: August 15, 2026

Accepted: August 26, 2026

Published online: September 21, 2026

Copyright: © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.

Publisher's Note: AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Keywords: Distributed acoustic sensing monitoring; Focal mechanism inversion; Double-couple model; Moment tensor model; General dislocation model

1. Introduction

In unconventional oil and gas development, hydraulic fracturing (HF) and microseismic monitoring are two key technologies for characterizing reservoir response and enhancing the efficiency of subsurface operations.¹⁻³ By injecting high-pressure fluids into target formations, HF creates and propagates fracture networks, thereby substantially improving reservoir permeability and enabling economic resource recovery.⁴ The injection-induced rock failure during HF operations naturally generates microseismic events (typically

with magnitudes $M < -3$). Microseismic focal mechanism analysis plays a critical role in characterizing fracture geometry, constraining in-situ stress states, and evaluating HF stimulation effectiveness.⁵⁻⁷

In microseismic studies, focal mechanisms are commonly represented using three primary source models: the double-couple (DC), general dislocation (GD), and moment tensor (MT) models.⁶ The DC and GD models are kinematic descriptions corresponding to pure shear and shear-tensile (or shear-compressive) slip on a fault plane, respectively, whereas the MT model characterizes the source mechanism through an equivalent force system.^{8,9} The DC model is inherently limited in its ability to capture non-DC components that may arise during HF stimulation, while MT inversion using data from a single well remains particularly challenging.^{10,11} Previous investigations have demonstrated that the GD model not only accommodates non-DC mechanisms but also yields relatively robust inversion results in downhole monitoring configurations.^{9,12,13} These studies highlight the importance of selecting an appropriate source parameterization for reliable microseismic focal mechanism inversion.

Conventionally, microseismic focal mechanisms are determined using 1-component or 3-component geophones deployed at the surface or in the monitoring wells. In recent years, distributed acoustic sensing (DAS) has emerged as an increasingly important alternative to conventional seismic geophones for HF microseismic monitoring.¹⁴⁻²² DAS sensors leverage elastic Rayleigh scattering in optical fibers and turn fibers into dense and continuous detectors that can measure strain over defined gauge lengths.^{23,24} Compared to conventional geophones, which are typically deployed at the surface or in adjacent monitoring wells, DAS fibers can be installed directly within HF treatment wells to acquire continuous, high-quality measurements with superior spatial and temporal resolution.²⁵ The high spatiotemporal resolution and favorable signal quality of DAS recordings enable detailed characterization of microseismic wavefields and facilitate improved assessment of HF stimulation effectiveness.¹⁴ Unlike geophone arrays, DAS sensors are sensitive to uniaxial strain (or strain rate) along the fiber orientation, yielding single-component (1C) measurements.²⁶ Several approaches have been proposed to mitigate this limitation, including the adoption of multi-component helical optical fibers,²⁷ the use of deviated or L-shaped array geometries,²⁸ and the deployment of DAS fibers across multiple wells.^{14,18}

Considerable progress has also been made in applying DAS to field microseismic monitoring. Lellouch *et al.*²⁹ compared the performance of a downhole DAS fiber-optic array with conventional geophones and demonstrated

its advantages in field geothermal monitoring. Verdon *et al.*²⁸ evaluated an L-shaped downhole DAS array against a surface array in field microseismic monitoring case studies, finding that the surface array detected significantly fewer events and yielded event locations with substantially greater scatter compared to the DAS array. Baird *et al.*²⁶ investigated the characteristics of DAS-recorded microseismic data in anisotropic media. Luo *et al.*¹⁸ assessed the feasibility of single-well dual-cable DAS for geothermal microseismic monitoring, reporting that the full MT can be resolved only at epicentral distances of 5 m or less, while non-DC components can be reliably resolved within an epicentral distance of 20 m. Wu *et al.*¹⁶ proposed a Hessian-based microseismic source mechanism inversion method and demonstrated its application to field HF DAS microseismic data processing.

Despite these advances, previous studies have largely focused either on comparing source models using conventional geophone data or on evaluating DAS acquisition and monitoring performance. A systematic comparison of the DC, GD, and MT source models specifically under DAS monitoring configurations, together with a comprehensive assessment of their inversion sensitivities, remains lacking. In particular, the effects of the 1C nature and directional sensitivity of DAS measurements on the relative performance of different source parameterizations have not been fully quantified. To address these gaps, this study presents a detailed comparison of the forward-modeling and inversion formulations of the DC, GD, and MT models and conducts numerical experiments to quantitatively evaluate their inversion performance in HF DAS monitoring. Specifically, we investigate the effects of DAS array orientation, input focal mechanism type, noise level, velocity model uncertainty, and source location error on inversion accuracy.

2. Methods

2.1. Forward modeling

The DC model⁸ assumes a pure shear faulting focal mechanism, whereas the GD model³⁰⁻³² is composed of both shear and tensile (or compressive) faulting. The MT model interprets focal mechanisms with equivalent forces and can represent all kinds of earthquakes.³³⁻³⁵

For the DC model, the source parameters are $(M_0, \kappa, \theta, \sigma)$, where M_0 is the scalar seismic moment, and κ, θ , and σ are the strike, dip, and rake (SDR) angles. The source parameters of the GD model are $(M_0, \kappa, \theta, \sigma, \alpha)$, in which $(M_0, \kappa, \theta, \sigma)$ are the same as those of the DC model, and α is the slope angle^{31,32}—the angle between $\mathbf{u}$ and $\mathbf{u}_{DC}$. The slope angle α ranges from -90° to 90° , negative for compressive faulting and positive for tensile faulting. The DC model

can be represented by the GD model in the case of $\alpha = 0^\circ$.

The MT model is represented by a seismic MT $\mathbf{M}$, i.e., a 3×3 symmetric matrix with six independent parameters ($M_{11}, M_{22}, M_{33}, M_{12}, M_{13}, M_{23}$)³³ (**Equation 1**):

$$\mathbf{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{bmatrix} \quad (1)$$

Following Tape and Tape,³⁶ the six parameters describing $\mathbf{M}$ (M_{ij} , $i, j = 1, 2, 3$) in **Equation 1** can be replaced by ($M_0, \kappa, \theta, \sigma, \gamma, \delta$), in which M_0 is the scalar seismic moment; κ, θ , and σ are the SDR angles; γ and δ are the longitude ($\gamma \in [-30^\circ, 30^\circ]$) and latitude ($\delta \in [-90^\circ, 90^\circ]$) on the eigenvalue lune that determine the MT pattern, respectively. Then $\mathbf{M}$ can be expressed as **Equation 2**:^{36,37}

$$\mathbf{M}(M_0, \gamma, \delta, \kappa, \theta, \sigma) = \sqrt{2}M_0 \cdot \mathbf{U}(\kappa, \theta, \sigma) \cdot \Lambda(\gamma, \delta) \cdot \mathbf{U}(\kappa, \theta, \sigma)^{-1} \quad (2)$$

where the matrix $\mathbf{U}$ parametrizes the MT orientations with the fault's SDR angles (**Equation 3**):

$$\mathbf{U} = \mathbf{Z}_{-\kappa} \cdot \mathbf{X}_\theta \cdot \mathbf{Z}_\sigma \cdot \mathbf{Y}_{-\pi/4} \quad (3)$$

in which $\mathbf{X}_\xi$, $\mathbf{Y}_\xi$, and $\mathbf{Z}_\xi$ are the rotation matrices through angle ξ (ξ can be any angle, e.g., θ , $(-\pi)/4$, $-\kappa$, or σ) about the x , y , and z coordinate axes, respectively (**Equation 4**):

$$\mathbf{X}_\xi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \xi & -\sin \xi \\ 0 & \sin \xi & \cos \xi \end{bmatrix}, \mathbf{Y}_\xi = \begin{bmatrix} \cos \xi & 0 & \sin \xi \\ 0 & 1 & 0 \\ -\sin \xi & 0 & \cos \xi \end{bmatrix}, \quad (4)$$

$$\mathbf{Z}_\xi = \begin{bmatrix} \cos \xi & -\sin \xi & 0 \\ \sin \xi & \cos \xi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Table 1 compares the DC, GD, and MT source models. In this paper, we used the same forward modeling method—the generalized reflection and transmission coefficient matrix method^{30,38–40}—to calculate the synthetic Green's functions and seismic waveforms for the DC, GD, and MT models. All the parameters of the three source models are transformed to MT parameters M_{ij} ($i, j = 1, 2, 3$) before inversion (transformations of DC and GD parameters referring to the paper^{30,31,33,41} and those of MT parameters referring to **Equations 1–4**^{36,37}).

2.2. Focal mechanism inversion

According to Section 2.1, the DC, GD, and MT models are represented by ($M_0, \kappa, \theta, \sigma$), ($M_0, \kappa, \theta, \sigma, \alpha$), and ($M_0, \kappa, \theta, \gamma, \delta$), respectively. The scalar seismic moment M_0 only corresponds to the absolute waveform amplitudes, and all

other parameters are angles, which have certain ranges ($\kappa \in [0^\circ, 360^\circ]$, $\theta \in [0^\circ, 90^\circ]$, $\sigma \in [-180^\circ, 180^\circ]$, $\alpha \in [-90^\circ, 90^\circ]$, $\gamma \in [-30^\circ, 30^\circ]$, and $\delta \in [-90^\circ, 90^\circ]$). Therefore, the focal mechanism parameters to be inverted can be separately reduced to (κ, θ, σ), ($\kappa, \theta, \sigma, \alpha$), and ($\kappa, \theta, \sigma, \gamma, \delta$) for these three models by using the misfit function under constraints of waveform similarity, polarity consistency, and S/P amplitude ratio between the observed and synthetic data.¹³ The DC, GD, and MT inversions were then implemented via a grid search algorithm to identify the optimal solution that minimizes the misfit function. Conventionally, MT inversion was performed using the generalized inverse method.⁴² In this study, however, the MT model was parameterized by ($M_0, \kappa, \theta, \gamma, \delta$), and its inversion was implemented using the same grid search algorithm as that adopted for the DC and GD models to eliminate result discrepancies arising from the use of different inversion algorithms. **Figure 1** illustrates the workflow of microseismic forward modeling and focal mechanism inversion based on the DC, GD, and MT source models employed in this study.

Table 1. Comparison of the double-couple (DC), general dislocation (GD), and moment tensor (MT) source models

Source models	DC	GD	MT
Physical process	Fault's shear slip	Fault's shear-tensile/compressive slip	Equivalent body forces
Number of parameters	4	5	6
Source parameters	$(M_0, \kappa, \theta, \sigma)$	$(M_0, \kappa, \theta, \sigma, \alpha)$	$(M_{11}, M_{22}, M_{33}, M_{12}, M_{13}, M_{23})$ or $(M_0, \kappa, \theta, \sigma, \gamma, \delta)$

Notes: M_0 denotes the scalar seismic moment, which is related to the seismic magnitude; κ, θ , and σ are the fault's strike, dip, and rake angles, respectively. α denotes the slope angle.^{31,32} $M_{11}, M_{22}, M_{33}, M_{12}, M_{13}, M_{23}$ denote the six parameters of the seismic MT, respectively; γ and δ are the longitude and latitude on the eigenvalue lune that determine the source pattern, respectively.^{36,37}

3. Numerical tests and results

3.1. Setup of the tests

The DAS monitoring configuration adopted for the numerical experiments in this study is illustrated in **Figure 2A**. Two orthogonal DAS arrays were deployed along the vertical and horizontal directions, designated as DAS-A and DAS-B, respectively. Each array comprises 10 sensor stations with a uniform spacing of 30 m. A representative

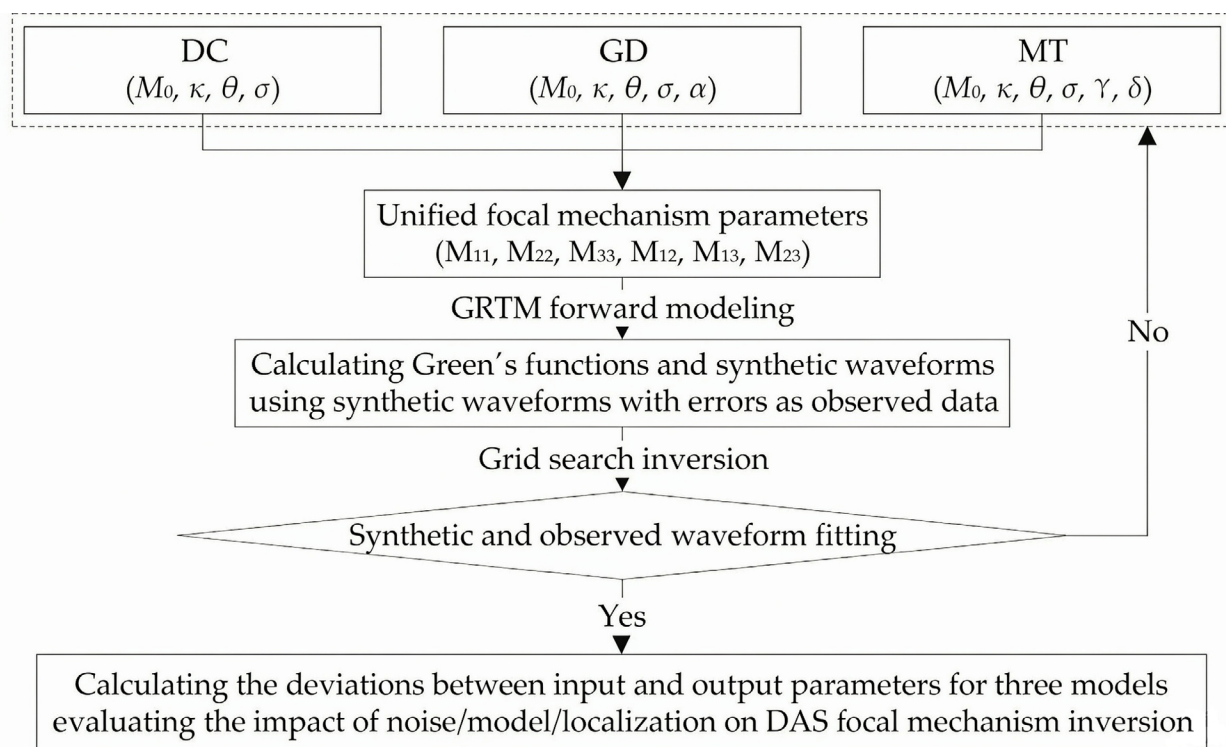


Figure 1. Workflow of microseismic forward modeling, focal mechanism inversion, and comparative analysis based on the DC, GD, and MT source models for DAS monitoring

Abbreviations: DAS: Distributed acoustic sensing; DC: Double-couple; GD: General dislocation; GRTM: Generalized reflection and transmission coefficient matrix; MT: Moment tensor.

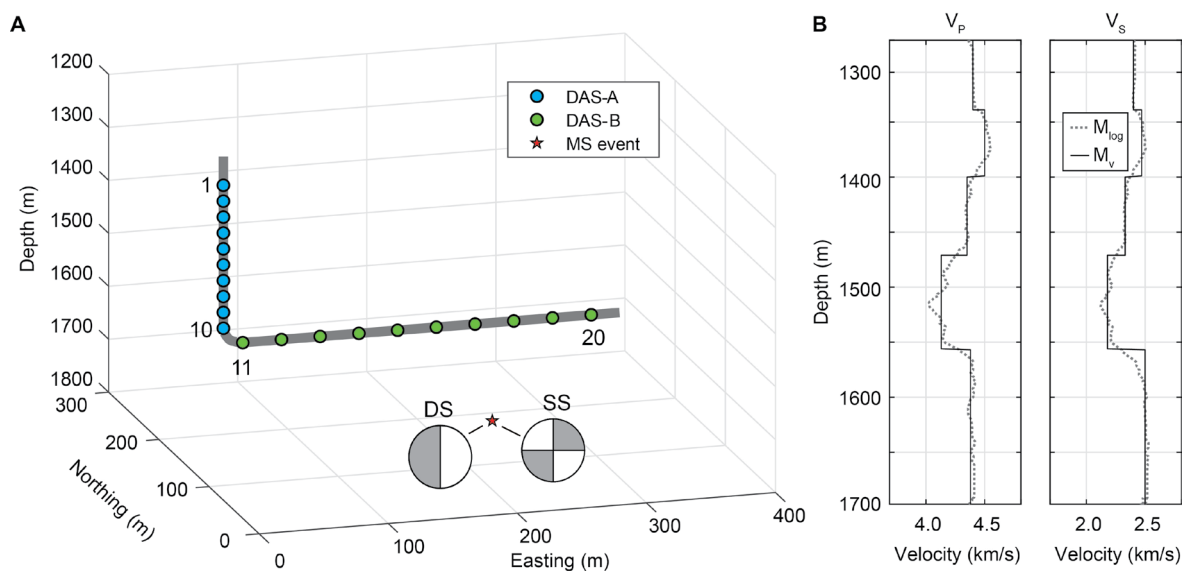


Figure 2. Distributed acoustic sensing (DAS) monitoring geometry, example microseismic (MS) event location, and P- and S-wave velocity models for the numerical experiments. (A) Blue and green dots represent DAS sensors deployed along the vertical and horizontal directions (DAS-A and DAS-B), respectively. Each array comprises 10 sensors (DAS-A: No. 1–10; DAS-B: No. 11–20) with a spacing of 30 m. The red star indicates the location of the example microseismic event. Focal mechanism beach balls illustrate the input strike-slip (SS) and dip-slip (DS) double-couple mechanisms, with (κ, θ, σ) values of $(0^\circ, 90^\circ, 0^\circ)$ and $(0^\circ, 90^\circ, 90^\circ)$, respectively. (B) Well-log data M_{log} (dotted lines) and velocity models M_v (straight lines). V_p and V_s denote the P- and S-wave velocities, respectively.

microseismic event is positioned at coordinates (200 m, 150 m, 1,670 m), corresponding to the west–east (X), south–north (Y), and vertical (Z) directions, respectively. Figure 2B presents the field well-log data and the derived P- and S-wave velocity models used in this study.

In field HF applications, strike-slip (SS) and dip-slip (DS) focal mechanisms are frequently observed.^{11,43,44} Accordingly, two representative input focal mechanisms were adopted for all numerical experiments: SS ($\kappa = 0$, $\theta = 90^\circ$, $\sigma = 0$) and DS ($\kappa = 0$, $\theta = 90^\circ$, $\sigma = 90^\circ$). Additional tests were also conducted using other mechanism types, including normal and reverse faulting. Conventional DAS fibers acquire 1C strain measurements along the fiber orientation.¹⁸ Consequently, in our numerical simulations, only the vertical Z-component waveforms were extracted for DAS-A, and the west–east component waveforms were

used for DAS-B, consistent with field DAS acquisition characteristics.

Figure 3 presents the synthetic waveforms recorded by DAS-A and DAS-B sensors for the SS source mechanism. As shown in Figure 3, the direct P- and S-wave waveforms across all 10 sensors in the DAS-A array exhibit similar morphologies, with variations primarily in amplitude. In contrast, the DAS-B array records waveforms that differ substantially in both polarity and amplitude across sensors. The inversion scheme employed in this study is constrained by waveform similarity, first-motion polarity consistency, and S/P amplitude ratio between observed and synthetic data. The high waveform diversity observed in the DAS-B array thus provides favorable constraints for microseismic focal mechanism inversion.

For downhole DAS monitoring data, generally only

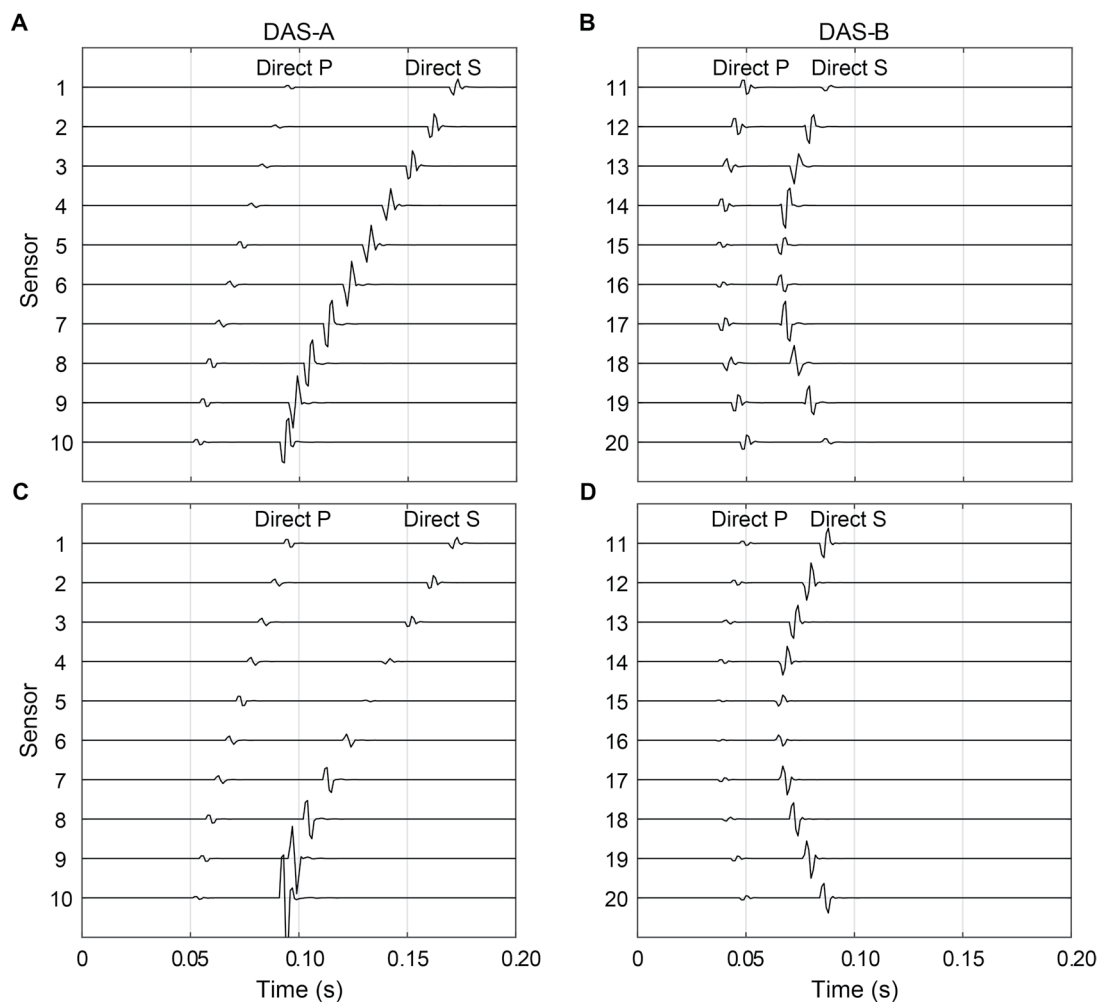


Figure 3. Synthetic waveforms generated for the input strike-slip (A–B) and dip-slip (C–D) sources. (A, C) The waveforms recorded by the distributed acoustic sensing (DAS)-A sensors. (B, D) Those recorded by the DAS-B sensors.

the first-arrival P- and S-waves are available for inversion; thus, only these two phase data are synthesized (Figure 3) and used for numerical tests. During inversion, the grid interval was set to 1°, and the search ranges for κ , θ , σ , γ , and δ were set as [0°, 360°], [0°, 90°], [−180°, 180°], [−90°, 90°], [−30°, 30°], and [−90°, 90°], respectively.

Commonly used DAS monitoring systems can be mainly divided into horizontal, vertical, and horizontal-vertical directions. In field cases, horizontal-vertical DAS geometry is usually adopted to make full use of the drilling well and obtain as much microseismic data as possible. In most numerical tests, we used both DAS-A and DAS-B (marked as DAS-A&B) to simulate microseismic waveforms. However, tests with different DAS directions (DAS-A, DAS-B, and DAS-A&B, Figure 2A) were also performed.

In downhole DAS monitoring, the data quality is usually extremely high due to the short source-receiver distances. Therefore, in most numerical tests, the field background records were scaled to 10% of the maximum peak amplitudes of the synthetic waveforms and then added to synthetic data as noise, corresponding to a noise level of 10%. In addition, tests with different noise levels are also performed.

Two parameters (ΔSDR and ΔDC^{13}) were used to evaluate the deviation between the input and output source parameters. ΔSDR indicates the total absolute deviation in the SDR angles, and ΔDC denotes the absolute misfit in the DC percentages. For the DC model, its DC percentage is 100%; thus, $\Delta\text{DC} = 0$. For the GD model, its DC percentage p^{DC} is obtained using the equation in the study by Vavryčuk³² (Equation 5):

$$p^{\text{DC}} = \frac{(1 - \sin|\alpha|)}{(\nu + 1)\sin|\alpha| + 1} \times 100\%, \quad (5)$$

where α is the slope angle, and $\nu = (V_p / V_s)^2 - 2$, in which V_p and V_s are P- and S-wave velocities. For the MT model, its DC percentages are calculated using the standard MT decomposition equations.^{33,45}

3.2. Impact of distributed acoustic sensing array orientation and comparison with three-component geophones

To investigate the influence of DAS array orientation on HF microseismic focal mechanism inversion, and to compare DAS-based inversions with inversions using conventional three-component (3C) geophones deployed at the same locations as the DAS sensors, we conducted numerical experiments using three configurations: Direction-A only, Direction-B only, and the combined Direction-A&B array.

These configurations correspond to DAS-A, DAS-B, and DAS-A&B in Figure 2A, respectively. The inversion results are presented in Figure 4.

As shown in Figure 4, all values of ΔSDR using DAS-A were greater than 20°, with the exception of the SS MT inversion. In contrast, the DC, GD, and SS MT inversions using DAS-B and DAS-A&B yield $\Delta\text{SDR} \leq 11^\circ$. The DC percentage deviations (ΔDC) of GD inversions are consistently below 12%, whereas those of MT inversions reach up to 32%. Overall, the combined DAS-A&B configuration produces smaller inversion deviations than either DAS-A or DAS-B alone. Accordingly, the DAS-A&B geometry was adopted as the monitoring configuration for all subsequent focal mechanism inversion experiments. In addition, the inversion deviations obtained using the DAS arrays were consistently larger than those with the 3C geophones.

3.3. Impact of input focal mechanism type

Various DC source mechanisms were employed as input parameters to assess the sensitivity of DAS-based focal mechanism inversion. In addition to the SS and DS mechanisms, we conducted tests using normal fault (strike = 0°, dip = 45°, rake = −90°) and reverse fault (strike = 0°, dip = 45°, rake = 90°) mechanisms. The DC, GD, and MT inversion results are summarized in Figure 5. As illustrated in Figure 5, all DC and GD inversion errors remain relatively small ($\Delta\text{SDR} \leq 10^\circ$ and $\Delta\text{DC} < 5\%$), whereas the angular misfits in MT inversions for DS and normal fault mechanisms are substantially larger ($\Delta\text{SDR} \geq 19^\circ$).

We also conducted GD and MT inversion tests using a range of non-DC focal mechanisms, whereas the DC inversion is restricted to pure DC sources. The input non-DC mechanisms were constructed by introducing nonzero slope angles into the SS and DS sources. From Equation 5, slope angles of $\pm 10^\circ$, $\pm 20^\circ$, $\pm 45^\circ$, and $\pm 90^\circ$ corresponded to DC percentages of 61%, 39%, 12%, and 0%, respectively. For MT mechanisms with slope angles of $\pm 90^\circ$, the SDR angles cannot be uniquely determined. Therefore, ΔSDR was not reported for these cases. The numerical test results are presented in Figure 6. As shown in the figure, the GD inversion errors remain consistently small for all tested non-DC mechanisms, with $\Delta\text{SDR} \leq 10^\circ$ and $\Delta\text{DC} < 5\%$. In contrast, some MT inversions for the DS-based non-DC mechanisms exhibited substantially larger angular misfits ($\Delta\text{SDR} \geq 14^\circ$).

3.4. Impact of noise level

Numerical experiments with varying noise levels (10%, 25%, and 40%) were performed to evaluate the robustness of DAS focal mechanism inversion under different signal-

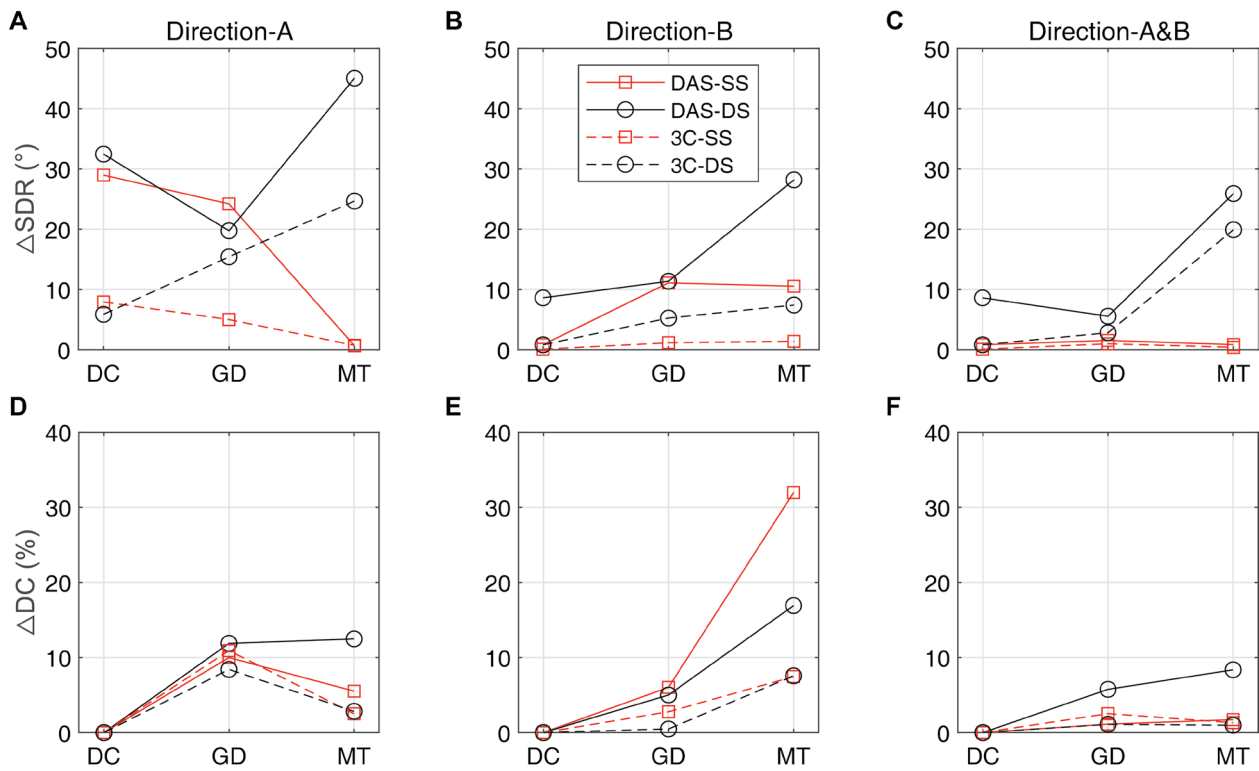


Figure 4. Inversion deviations of (A–C) strike, dip, and rake (SDR) angles (ΔSDR) and (D–F) double-couple (DC) percentage deviations (ΔDC) for the DC, general dislocation (GD), and moment tensor (MT) models using different distributed acoustic sensing (DAS) array orientations (solid lines) and three-component (3C; dashed lines) geophones. Direction-A, Direction-B, and Direction-A&B indicate the same locations as those of DAS-A, DAS-B, and DAS-A&B in Figure 2A, respectively. Each inversion was performed with 10% field noise added to the synthetic waveforms. $\Delta\text{SDR} = |\Delta\kappa| + |\Delta\theta| + |\Delta\sigma|$, where $|\Delta\kappa|$, $|\Delta\theta|$, and $|\Delta\sigma|$ represent the absolute deviations between input and inverted SDR angles, respectively. ΔDC denotes the absolute difference between input and inverted DC percentages. Red and black lines represent inversion results for input strike-slip (SS; strike = 0°, dip = 90°, rake = 0°) and dip-slip (DS; strike = 0°, dip = 90°, rake = 90°) focal mechanisms, respectively.

to-noise conditions. Figure 7 presents the DC, GD, and MT inversion results. As observed in Figure 7, both angular and percentage deviations increased progressively with noise level from 10% to 25% to 40%. For a given noise level, the inversion misfit generally increased in the order of DC $\rightarrow$ GD $\rightarrow$ MT. Overall, the DC and GD inversions maintained relatively small errors ($\Delta\text{SDR} \leq 21^\circ$ and $\Delta\text{DC} < 5\%$) even at noise levels as high as 40%, whereas MT inversions began to deviate substantially from the true solution at noise levels as low as 10%.

3.5. Impact of velocity model uncertainty

In field DAS data processing, obtaining an accurate velocity model is often difficult. Therefore, it is essential to evaluate the resolvability of microseismic focal mechanisms in the presence of velocity model inaccuracies. For the numerical experiments, two velocity models with 5% and 10% random perturbations were employed for forward modeling. Since velocity errors may introduce time shifts

between synthetic waveforms computed with accurate and inaccurate models, we adopted an inversion strategy based on the Cut-and-Paste method⁴⁶ to mitigate the impact of velocity uncertainties. Figure 8 shows the inversion results with 5% and 10% velocity errors. The results show that MT inversions exhibited significant deviations from the input under 10% velocity error, whereas DC and GD inversions maintained relatively small errors ($\Delta\text{SDR} \leq 20^\circ$ and $\Delta\text{DC} < 10\%$).

3.6. Impact of source location uncertainty

We further conducted numerical experiments to assess the impact of source location errors on focal mechanism inversion. Three perturbed source locations were tested, corresponding to errors in the horizontal, vertical, and combined horizontal-vertical coordinates relative to the reference event in Figure 2A: S1 (200 m, 240 m, 1670 m) with 10 m horizontal error, S2 (200 m, 250 m, 1660 m) with 10 m depth error, and S3 (200 m, 240 m, 1660 m) with

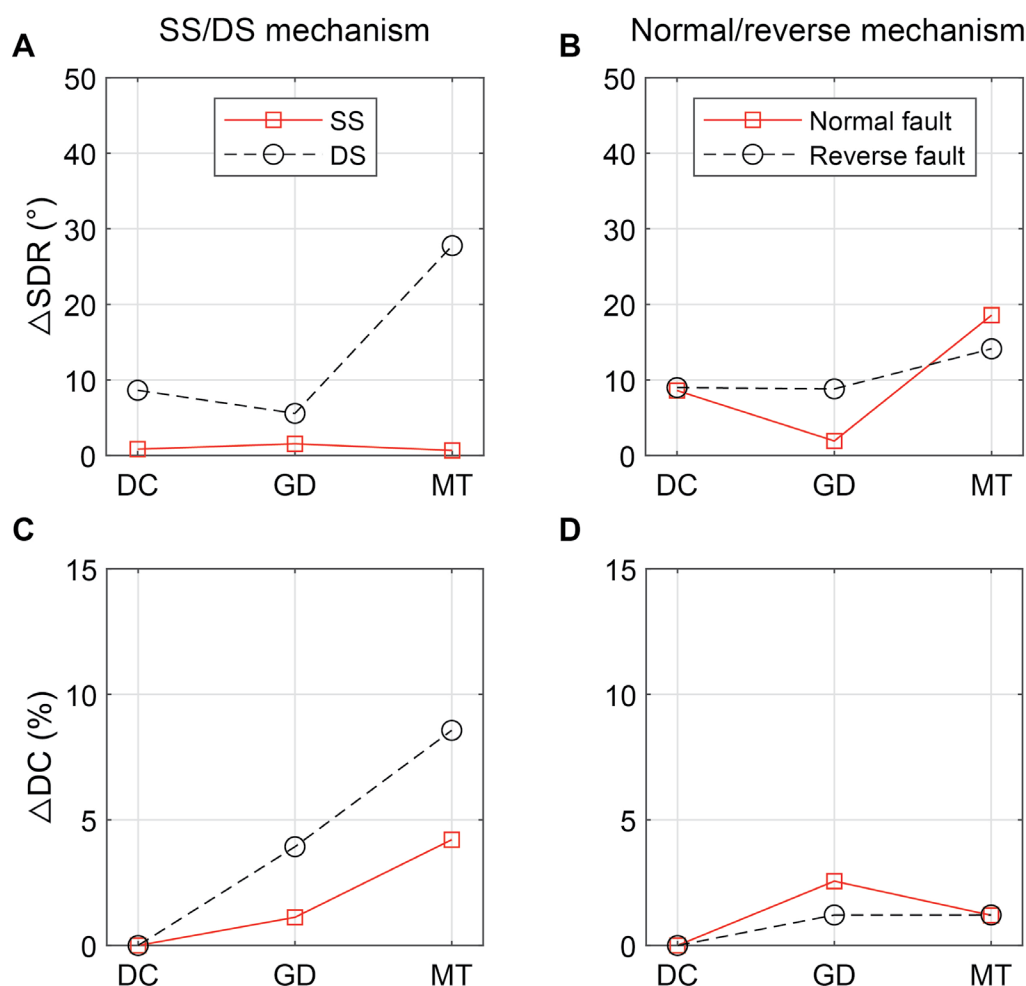


Figure 5. Inversion deviations of (A, B) strike, dip, and rake angles (ΔSDR) and (C, D) double-couple (DC) percentage deviations (ΔDC) for the DC, general dislocation (GD), and moment tensor (MT) models using different input DC focal mechanisms. Each inversion was performed with 10% field noise added to the synthetic waveforms. Red solid lines and black dashed lines in (A) and (C) represent inversion results for input strike-slip (SS) and dip-slip (DS) mechanisms, respectively. Red solid lines and black dashed lines in (B) and (D) represent inversion results for input normal fault (strike = 0°, dip = 45°, rake = -90°) and reverse fault (strike = 0°, dip = 45°, rake = 90°) mechanisms, respectively.

20 m total location error. The DC, GD, and MT inversion results are presented in Figure 9. The results indicate that all DC and GD inversion misfits remained relatively small ($\Delta SDR \leq 10^\circ$ and $\Delta DC < 10\%$), whereas only two out of the six MT inversion tests showed deviations at this level.

4. Discussion

In this study, we conducted systematic numerical experiments using a downhole DAS monitoring configuration to investigate the microseismic focal mechanism inversion sensitivity of the DC, GD, and MT source models. The effects of DAS array orientation, input focal mechanism type, noise level, velocity model uncertainty, and source location error on DAS-based

inversion are systematically evaluated. Our findings can be summarized as follows:

- (i) The inversion errors obtained using the DAS arrays are generally larger than those obtained using conventional 3C geophones (Figure 4). This likely reflects that conventional DAS measurements are primarily sensitive to axial strain (or strain rate) along the fiber direction and therefore provide only 1C observations. Compared to 3C geophones, DAS records contain less directional information and impose fewer independent constraints on the source radiation pattern. This limitation becomes particularly important for MT inversion, which involves six independent source parameters. Fewer observational

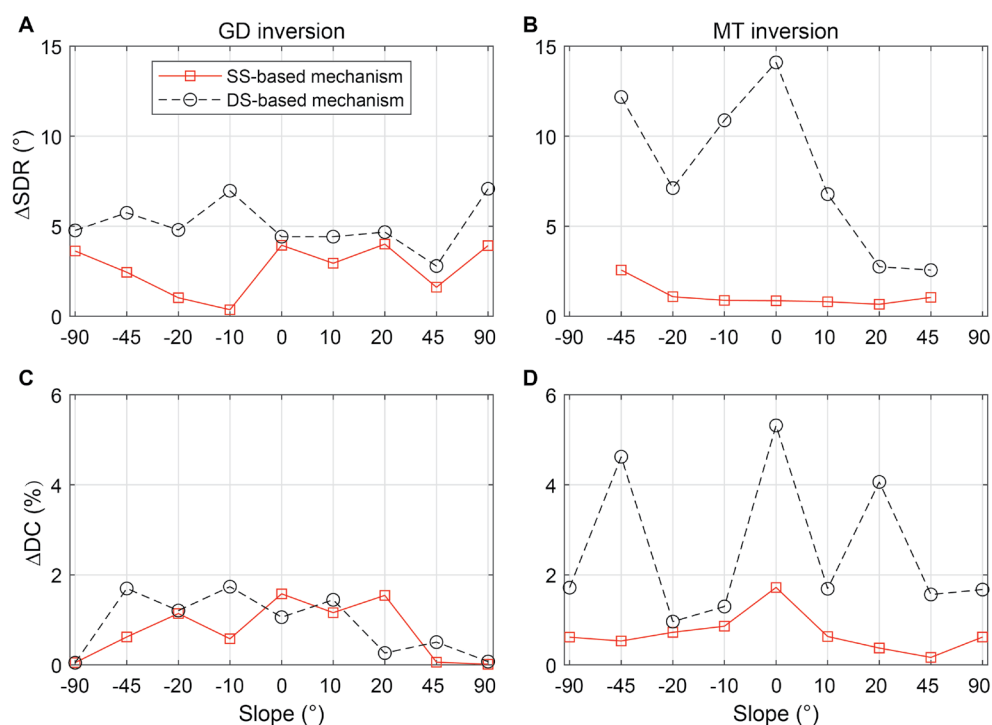


Figure 6. Inversion deviations of (A, B) strike, dip, and rake angles (ΔSDR) and (C, D) double-couple (DC) percentage deviations (ΔDC) for the general dislocation (GD) and moment tensor (MT) models using different input non-DC focal mechanisms. Each inversion was performed with 10% field noise added to the synthetic waveforms. Red solid lines and black dashed lines represent inversion results for input strike-slip (SS) and dip-slip (DS) based focal mechanisms, respectively.

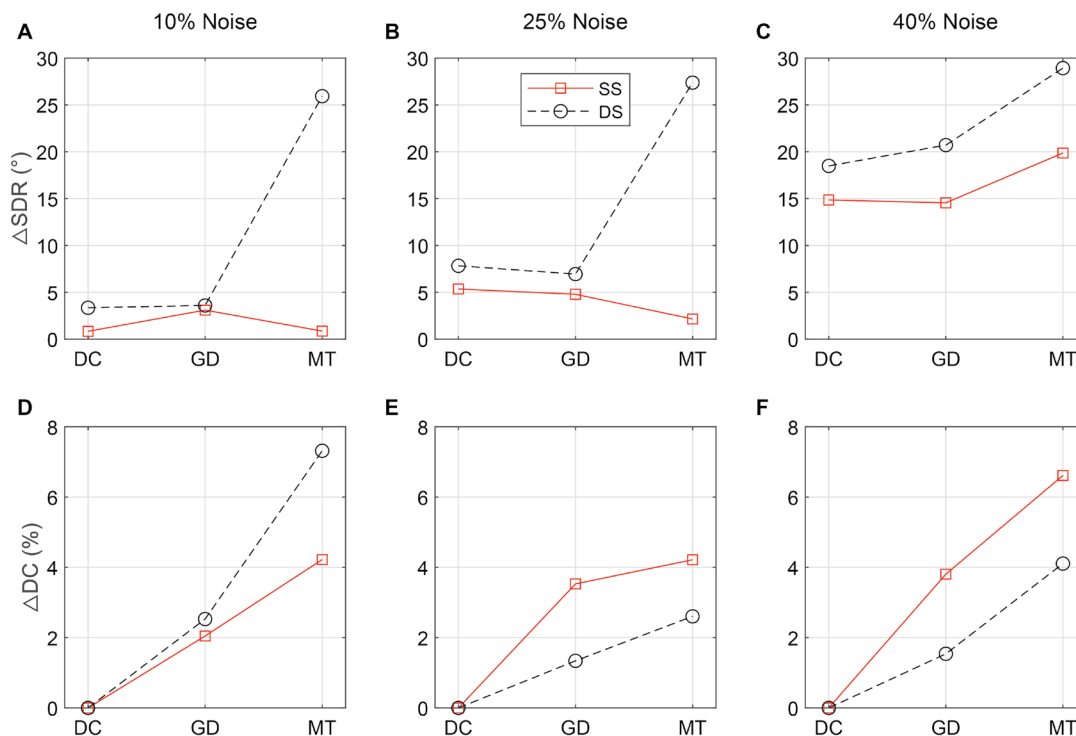


Figure 7. Inversion deviations of (A–C) strike, dip, and rake angles (ΔSDR) and (D–F) double-couple (DC) percentage deviations (ΔDC) for the DC, general dislocation (GD), and moment tensor (MT) models at different noise levels. Field background noise was added to the synthetic microseismic waveforms. Red solid lines and black dashed lines represent inversion results for input strike-slip (SS) and dip-slip (DS) focal mechanisms, respectively.

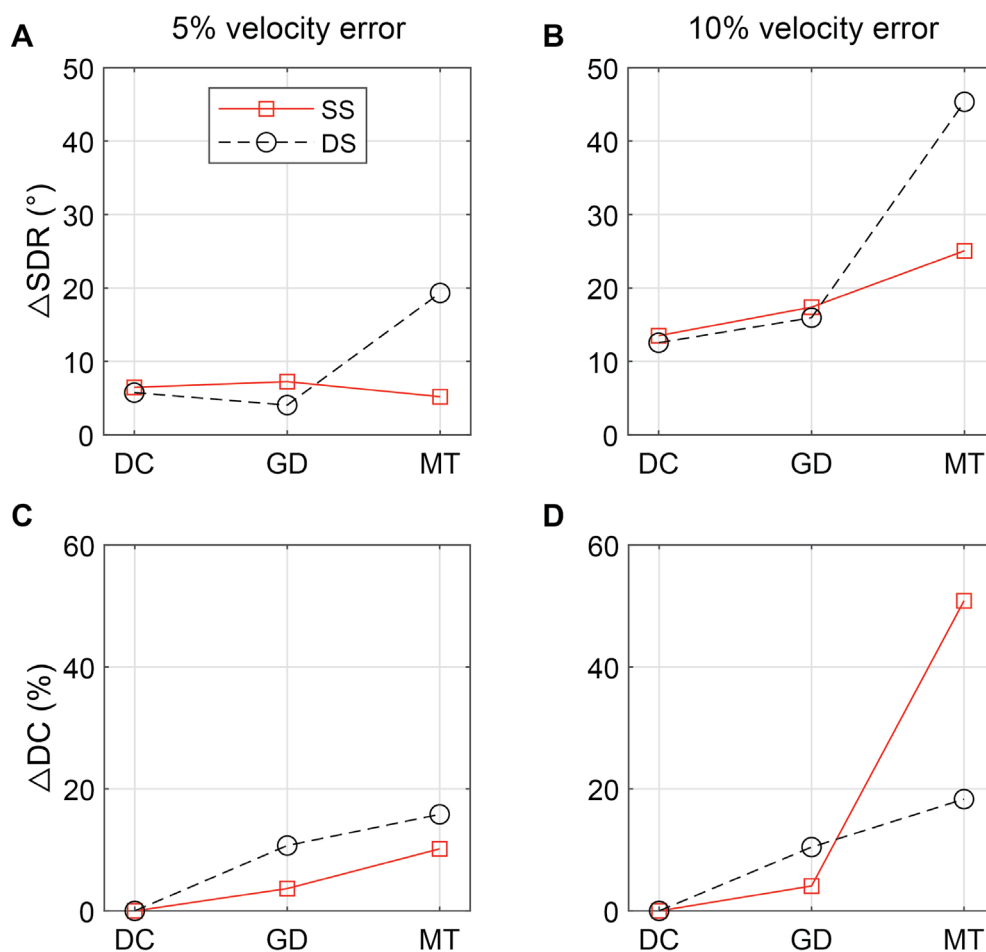


Figure 8. Inversion deviations of (A, B) strike, dip, and rake angles (ΔSDR) and (C, D) double-couple (DC) percentage deviations (ΔDC) for the DC, general dislocation (GD), and moment tensor (MT) models using velocity models with 5% and 10% random errors. Each inversion was performed with 10% field noise added to the synthetic waveforms. Red solid lines and black dashed lines represent inversion results for input strike-slip (SS) and dip-slip (DS) focal mechanisms, respectively.

constraints increase parameter trade-offs and the non-uniqueness of the inverse problem, exacerbating ill-posedness and increasing inversion uncertainties.

- (ii) The majority of inversion errors (ΔSDR and ΔDC ; Figures 4–8) increase progressively across the three models in the order of DC→GD→MT. This trend is consistent with previous studies based on conventional geophone data,^{12,13,47,48} and is likely attributable to the increasing complexity of the source models, as reflected by the growing number of free parameters (4→5→6; Table 1). For DAS observations, this effect can be further amplified by the limited directional information inherent in 1C measurements. As the number of free source parameters increases, particularly for the six-parameter MT model, stronger trade-offs among the MT components may arise, making the inverse problem more weakly constrained

and ill-conditioned. Consequently, the MT inversion is more sensitive to limited observational constraints and tends to exhibit larger inversion errors than the more strongly constrained DC and GD inversions.

- (iii) As shown in Figure 4, DAS arrays with better horizontal source-receiver azimuthal coverage (DAS-B and DAS-A&B) yield more robust inversion results than those with limited horizontal coverage (DAS-A). The DAS-A configuration represents a single-well downhole observation system, for which focal mechanism inversion has long been recognized as particularly challenging.^{10,11,18} Since focal mechanism inversion is constrained by first-motion polarity and waveform fitting between observed and synthetic seismograms, monitoring geometries with broader source-receiver coverage provide more diverse P and S wavefield information (Figure 3), thereby facilitating

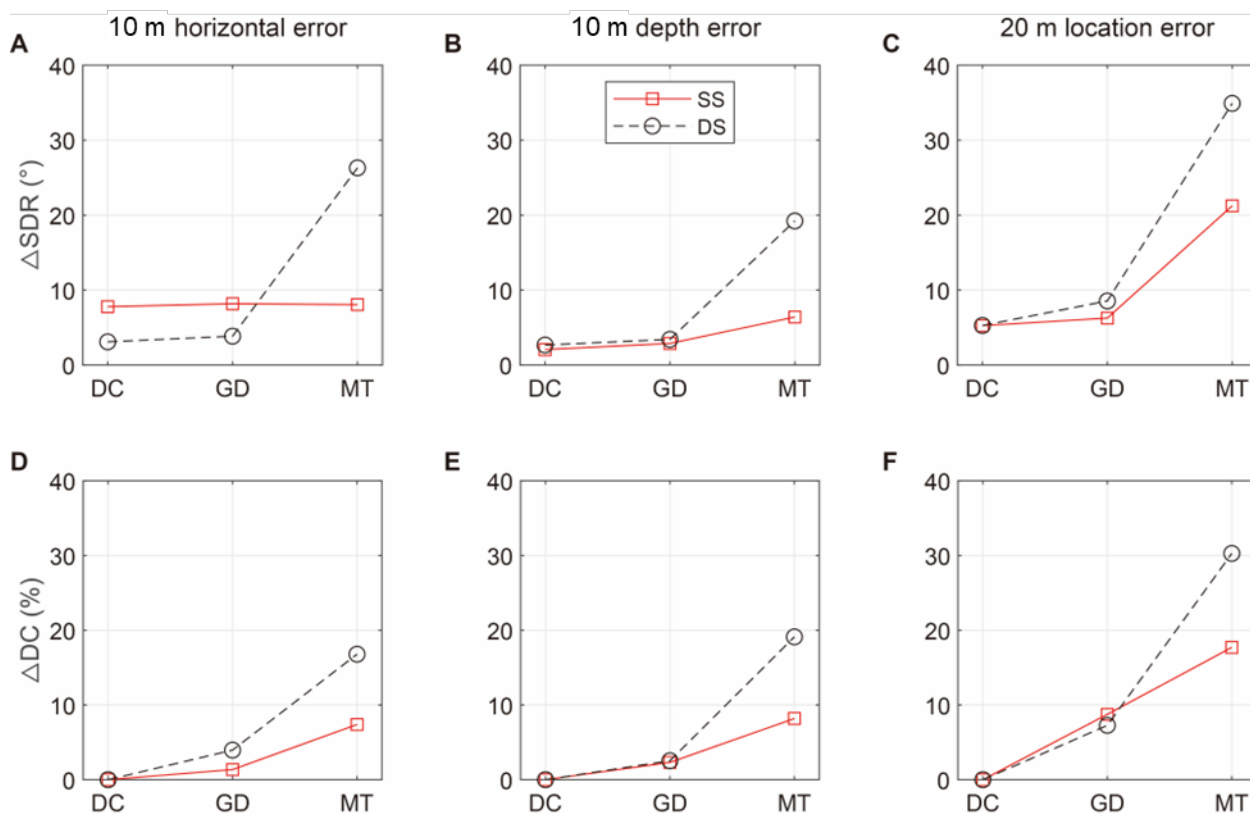


Figure 9. Inversion deviations of (A–C) strike, dip, and rake angles (ΔSDR) and (D–F) DC percentage deviations (ΔDC) for the DC, general dislocation (GD), and moment tensor (MT) models using source locations with horizontal, vertical, or combined horizontal and vertical errors. Each inversion was performed with 10% field noise added to the synthetic waveforms. Red solid lines and black dashed lines represent inversion results for input strike-slip (SS) and dip-slip (DS) focal mechanisms, respectively.

more accurate inversion results.

- (iv) For the horizontal-vertical DAS monitoring configuration (DAS-A&B), all DC and GD inversions yield physically reasonable solutions. In contrast, the MT model exhibits significant inversion misfits ($\Delta\text{SDR} > 25^\circ$ or $\Delta\text{DC} > 20\%$) in tests involving DS mechanisms, noise levels of 10%, 25%, and 40%, 10% velocity errors, and 10 m source location errors. Some MT inversion deviations are particularly large, reaching ΔSDR values of $\sim 50^\circ$ and ΔDC values of $\sim 50\%$. This indicates that MT inversion in DAS monitoring is less stable and more susceptible to perturbations compared to DC and GD inversions—a finding that is also consistent with microseismic focal mechanism studies using traditional geophones.¹³

It should be noted that the numerical experiments in this study assume accurate P- and S-wave arrival picking. In practice, picking uncertainties in field DAS data may affect both microseismic event location and waveform alignment, thereby influencing the accuracy of focal mechanism

inversion. The combined effects of these uncertainties are not explicitly investigated in the present study and will be further evaluated using field DAS data in future work. In addition, all simulations in this study are conducted under the assumption of isotropic media. In practice, shale reservoirs may exhibit significant seismic anisotropy, which could affect waveform characteristics and consequently the accuracy of microseismic focal mechanism inversion. Numerical experiments incorporating shale anisotropy, together with further validation of the proposed approach using field DAS observations, should be considered in future work.

5. Conclusion

In this study, we present a systematic comparison of the DC, GD, and MT source models for HF microseismic monitoring using DAS data. Numerical experiments are conducted to evaluate their performance in DAS-based microseismic focal mechanism inversion. All synthetic seismograms are generated using the generalized reflection

and transmission coefficient matrix method, with field background noise added to simulate realistic field observations. Our results demonstrate that downhole DAS focal mechanism inversion is strongly controlled by the horizontal azimuthal coverage of source-receiver geometry. For the horizontal-vertical DAS monitoring configuration, MT inversion exhibits significant deviations from the true solution when subjected to DS input mechanisms, 5% velocity model errors, 10 m source location uncertainties, or 40% noise levels, whereas both DC and GD inversions maintain robust performance under these conditions. Given that HF operations can induce microseismic events with non-DC components, the GD model-based inversion represents a reliable approach for obtaining accurate focal mechanisms in horizontal-vertical DAS monitoring scenarios, thereby advancing the application and reliability of DAS technology for microseismic monitoring.

Acknowledgments

None.

Funding

This research was funded by the National Key Research and Development Program of China (2023YFF0615101), the Scientific Research and Technology Development Project of China National Petroleum Corporation (2024DQ0536, 2023ZZ28YJ03, and 2026DQ03020) the Key Research and Development Program of Shaanxi Province (2026CY-ZDGG-22), and the Science and Technology Project of China National Logging Corporation (25ZYCJSG010-2503).

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Quanlong He

Formal analysis: Xiaodong Wang, Zhao Han

Investigation: Quanlong He, Shuaihong Liu, Shaowei Sun, Yuqi Cheng

Methodology: Quanlong He, Tao Chen, Guoquan Liu

Writing—original draft: Quanlong He

Writing—review & editing: Shuaihong Liu, Tao Chen, Shaowei Sun, Yuqi Cheng, Guoquan Liu, Xiaodong Wang, Zhao Han

Availability of data

Data are available from the corresponding author upon reasonable request.

References

1. Maxwell S. Microseismic: Growth born from success. *Lead Edge*. 2010;29(3):338-343.
doi: 10.1190/1.3353732
2. Ma Y, Eaton DW, Wang C, Aklilu A. Characterizing hydraulic fracture growth using distributed acoustic sensing-recorded microseismic reflections. *Geophysics*. 2023;88(6):WC47-WC57.
doi: 10.1190/geo2022-0607.1
3. Gao Y, Tilmann F, Yuan X, *et al.* Unraveling the Mantle Dynamics in Central Asia With Joint Full Waveform Inversion. *J Geophys Res Solid Earth*. 2025;130(2):e2024JB030061.
doi: 10.1029/2024JB030061
4. Maxwell S. Microseismic hydraulic fracture imaging: The path toward optimizing shale gas production. *Lead Edge*. 2011;30(3):340-346.
doi: 10.1190/1.3567266
5. Baig A, Urbancic T. Microseismic moment tensors: A path to understanding frac growth. *Lead Edge*. 2010;29(3):320-324.
doi: 10.1190/1.3353729
6. Li H, Chang X. A review of the microseismic focal mechanism research. *Sci China Earth Sci*. 2021;64(3):351-363.
doi: 10.1007/s11430-020-9658-7
7. Wamriew D, Dorhjie DB, Bogoeodov D, *et al.* Microseismic Monitoring and Analysis Using Cutting-Edge Technology: A Key Enabler for Reservoir Characterization. *Remote Sens*. 2022;14(14):3417.
doi: 10.3390/rs14143417
8. Aki K, Richards PG. *Quantitative Seismology*. 2nd ed. Sausalito, CA: University Science Books; 2002.
9. Šílený J, Horálek J. Shear-tensile crack as a tool for reliable estimates of the non-double-couple mechanism: West Bohemia-Vogtland earthquake 1997 swarm. *Phys Chem Earth*. 2016;95:113-124.
doi: 10.1016/j.pce.2016.06.007
10. Eaton DW, Forouhideh F. Solid angles and the impact of receiver-array geometry on microseismic moment-tensor inversion. *Geophysics*. 2011;76(6):WC77-WC85.
doi: 10.1190/geo2011-0077.1
11. Eyre TS, van der Baan M. The reliability of microseismic moment-tensor solutions: Surface versus borehole monitoring. *Geophysics*. 2017;82(6):KS113-KS125.

- doi: 10.1190/GEO2017-0056.1
12. Šílený J. Resolution of non-double-couple mechanisms: Simulation of hypocenter mislocation and velocity structure mismodeling. *Bull Seismol Soc Am.* 2009;99(4):2265-2272.
doi: 10.1785/0120080335
 13. Li H, Chang X, Hao J, Wang Y. Comparison of Single-Well Microseismic Focal Mechanism Inversions with Different Source Models. *Bull Seismol Soc Am.* 2021;111(6):3103-3117.
doi: 10.1785/0120210070
 14. Staněk F, Jin G, Simmons J. Fracture Imaging Using DAS-Recorded Microseismic Events. *Front Earth Sci.* 2022;10:907749.
doi: 10.3389/feart.2022.907749
 15. Wu S, Wang Y, Liang X. Time-Delay Estimation of Microseismic DAS Data Using Band-Limited Phase-Only Correlation. *IEEE Trans Geosci Remote Sens.* 2023;61:1-9.
doi: 10.1109/TGRS.2022.3229685
 16. Wu S, Wang Y, Liang X. Hydraulic fracturing distributed acoustic sensing monitoring data source mechanism inversion: A Hessian-based method. *Geophysics.* 2023;88(6):WC133-WC143.
doi: 10.1190/geo2023-0073.1
 17. Rodriguez IV, Podrasky D, Coleman T, Maldaner C, Ma Y, Ajo-franklin J. DAS Moment Magnitude Calculation in the Time Domain for General Dislocations: Application at Utah FORGE. *Bull Seismol Soc Am.* 2025;115(6):2592-2607.
doi: 10.1785/0120250084
 18. Luo W, Drijkoningen G, Eltayieb M, Amann F, Vardon PJ. Feasibility Study of Single-Well Dual-Cable DAS for Microseismic Monitoring of Geothermal Operations. *Rock Mech Rock Eng.* 2025;59:2811-2837.
doi: 10.1007/s00603-025-04942-6
 19. Karrenbach M, Ridge A, Cole S, *et al.* DAS Microseismic Monitoring and Integration With Strain Measurements in Hydraulic Fracture Profiling. In: *Proceedings of the 5th Unconventional Resources Technology Conference*. Tulsa, OK: American Association of Petroleum Geologists; 2017.
doi: 10.15530/urtec-2017-2670716
 20. Karrenbach M, Cole S, Ridge A, *et al.* Fiber-optic distributed acoustic sensing of microseismicity, strain and temperature during hydraulic fracturing. *Geophysics.* 2018;84(1):D11-D23.
doi: 10.1190/geo2017-0396.1
 21. Daley TM, Freifeld BM, Ajo-Franklin J, *et al.* Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring. *Lead Edge.* 2013;32(6):699-706.
doi: 10.1190/tle32060699.1
 22. Zhang Z, White MCA, Bai T, Qiu H, Nakata N. Characterizing Microearthquakes Induced by Hydraulic Fracturing With Hybrid Borehole DAS and Three-Component Geophone Data. *IEEE Trans Geosci Remote Sens.* 2023;61:1-15.
doi: 10.1109/TGRS.2023.3264931
 23. Rashid A, Tackie-Otoo BN, Abdul Latiff AH, Otchere DA, Jamaludin SNF, Asfha DT. Research Advances on Distributed Acoustic Sensing Technology for Seismology. *Photonics.* 2025;12(3):196.
doi: 10.3390/photonics12030196
 24. Becker MW, Ciervo C, Cole M, Coleman T, Mondanos M. Fracture hydromechanical response measured by fiber optic distributed acoustic sensing at milliHertz frequencies. *Geophys Res Lett.* 2017;44(14):7295-7302.
doi: 10.1002/2017GL073931
 25. Mad Zahir MH, Abdul Aziz KM, Ghazali AR, Abdul Latiff AH. Effectiveness of Fiber Optic Distributed Acoustic Sensing (DAS) in Vertical Seismic Profiling (VSP) Field Survey. *Appl Sci.* 2023;13(8):5002.
doi: 10.3390/app13085002
 26. Baird AF, Stork AL, Horne SA, *et al.* Characteristics of microseismic data recorded by distributed acoustic sensing systems in anisotropic media. *Geophysics.* 2020;85(4):KS139-KS147.
doi: 10.1190/geo2019-0776.1
 27. Lim Chen Ning I, Sava P. High-resolution multi-component distributed acoustic sensing. *Geophys Prospect.* 2018;66(6):1111-1122.
doi: 10.1111/1365-2478.12634
 28. Verdon JP, Horne SA, Clarke A, Stork AL, Baird AF, Kendall JM. Microseismic monitoring using a fiber-optic distributed acoustic sensor array. *Geophysics.* 2020;85(3):KS89-KS99.
doi: 10.1190/geo2019-0752.1
 29. Lellouch A, Lindsey NJ, Ellsworth WL, Biondi BL. Comparison between distributed acoustic sensing and geophones: Downhole microseismic monitoring of the FORGE geothermal experiment. *Seismol Res Lett.* 2020;91(6):3256-3268.
doi: 10.1785/0220200149
 30. Li H, Chang X, Hao J, Wang Y. The general dislocation source model and its application to microseismic focal mechanism inversion. *Geophysics.* 2021;86(4):KS79-KS93.
doi: 10.1190/GEO2020-0844.1
 31. Vavryčuk V. Tensile earthquakes: Theory, modeling, and inversion. *J Geophys Res Solid Earth.* 2011;116(B12):B12320.
doi: 10.1029/2011JB008770
 32. Vavryčuk V. Inversion for parameters of tensile earthquakes. *J Geophys Res Solid Earth.* 2001;106(B8):16339-16355.

- doi: 10.1029/2001JB000372
33. Jost ML, Herrmann RB. A Student's Guide to and Review of Moment Tensors. *Seismol Res Lett*. 1989;60(2):37-57.
doi: 10.1785/gssrl.60.2.37
 34. Julian BR, Miller AD, Foulger GR. Non-double-couple earthquakes (1) theory. *Rev Geophys*. 1998;36(4):525-549.
doi: 10.1029/98RG00716
 35. Miller AD, Foulger GR, Julian BR. Non-double-couple earthquakes (2) observations. *Rev Geophys*. 1998;36(4):551-568.
doi: 10.1029/98RG00717
 36. Tape W, Tape C. A geometric comparison of source-type plots for moment tensors. *Geophys J Int*. 2012;190(1):499-510.
doi: 10.1111/j.1365-246X.2012.05490.x
 37. Tape W, Tape C. A uniform parametrization of moment tensors. *Geophys J Int*. 2015;202(3):2074-2081.
doi: 10.1093/gji/ggv262
 38. Langston CA. Source inversion of seismic waveforms: The Koyana, India, earthquakes of 13 September 1967. *Bull Seismol Soc Am*. 1981;71(1):1-24.
doi: 10.1785/bssa0710010001
 39. Yao ZX, Harkrider DG. A generalized reflection-transmission coefficient matrix and discrete wavenumber method for synthetic seismograms. *Bull Seismol Soc Am*. 1983;73(6A):1685-1699.
 40. Zhu L, Rivera LA. A note on the dynamic and static displacements from a point source in multilayered media. *Geophys J Int*. 2002;148(3):619-627.
doi: 10.1046/j.1365-246X.2002.01610.x
 41. Ou GB. Seismological studies for tensile faults. *Terr Atmos Ocean Sci*. 2008;19(5):463-471.
doi: 10.3319/TAO.2008.19.5.463(T)
 42. Song F, Toksöz MN. Full-waveform based complete moment tensor inversion and source parameter estimation from downhole microseismic data for hydrofracture monitoring. *Geophysics*. 2011;76(6):WC103-WC116.
doi: 10.1190/geo2011-0027.1
 43. Eisner L, Williams-Stroud S, Hill A, Duncan P, Thornton M. Beyond the dots in the box: Microseismicity-constrained fracture models for reservoir simulation. *Lead Edge*. 2010;29(3):326-333.
doi: 10.1190/1.3353730
 44. Staněk F, Eisner L, Jan Moser T. Stability of source mechanisms inverted from P-wave amplitude microseismic monitoring data acquired at the surface. *Geophys Prospect*. 2014;62(3):475-490.
doi: 10.1111/1365-2478.12107
 45. Vavryčuk V. Moment tensor decompositions revisited. *J Seismol*. 2015;19(1):231-252.
doi: 10.1007/s10950-014-9463-y
 46. Zhu L, Zhou X. Seismic moment tensor inversion using 3D velocity model and its application to the 2013 Lushan earthquake sequence. *Phys Chem Earth*. 2016;95:10-18.
doi: 10.1016/j.pce.2016.01.002
 47. Stierle E, Vavryčuk V, Šílený J, Bohnhoff M. Resolution of non-double-couple components in the seismic moment tensor using regional networks-i: A synthetic case study. *Geophys J Int*. 2014;196(3):1869-1877.
doi: 10.1093/gji/ggt502
 48. Šílený J. Shear-tensile/Implosion Source Model vs. Moment Tensor - Benefit in Single-azimuth Monitoring, Cotton Valley Setup. In: *Proceedings*. Houten, Netherlands: EAGE Publications BV; 2012.
doi: 10.3997/2214-4609.20148211