Journal of Environmental Science and Engineering B 14 (2025) 155-169
doi:10.17265/2162-5263/2025.04.002

Test and Development of Microseismic Monitoring

Beiyuan Liang
GeoImage LLC, San Francisco, CA 94118, USA

Abstract: This is a continuation of the article "Ground Monitoring of Microseismic Based on Low Signal-to-Noise Ratio", and a further summary and reflection after investigating the current situation of microseismic monitoring. It is difficult to provide necessary and sufficient conditions to test the reliability of microseismic monitoring. Often, a few hundred meters away, the microseismic signal emitted by a hypocenter is submerged in noise, and the traditional location is invalid; Inversion for microseismic released energy distribution using data migration and stacking is in principle not unique. However, based on microseismic monitoring characteristics, forward and reverse simulations and numerous experiments, many necessary conditions can be proposed to ensure reliable monitoring with high probability. VS (Vector Scanning) ground monitoring for microseismic proposes eight necessary conditions for testing the reliability, so that VS finds the fracturing-induced effective communication seam with the characteristics of shear zones under the control of tectonic stress fields, in line with the laws of seismic and geological observations, as well as the features related to some special production data. VS uses data migration and stacking suitable for low signal-to-noise ratio and shear mechanism, and the joint inversion for correction of both traditional relocations and velocity model, can greatly improve monitoring distance and quality, complete microseismic measurement methods, and broaden applicable fields, such as: (1) VS can be a cost-effective, ground-based, routine monitoring method; (2) The BPM (Borehole Proximity Monitoring) is high cost but close to the hypocenters; It can be the best method for scientific research, but its seismic network should be improved, and the joint inversion and data stacking could be used to improve the monitoring distance and quality; (3) The early warning of mine safety can change the current monitoring of strong microseismic (or accidents have been happened) to the real microseismic level; and (4) The seismic precursor monitoring of large earthquakes can be expanded from small earthquakes to microseismic. These will establish a solid foundation and complete seismic measurements for microseismology.

Keywords: Microseismic, vector-stacking, focal-mechanism, test, development.

1. Introduction

The article "Ground Monitoring of Microseismic Based on Low Signal-to-Noise Ratio" [1] investigated the current situation of microseismic monitoring, and introduced the ground monitoring of microseismic VS (Vector Scanning). We assume that the reader has read this article. This paper further summarizes and thinks about the inspection and development of microseismic monitoring, and including some supplement to the status.

Developing any technical method, even its each step, should have the conditions for verification to determine its reliability. To judge the reliability of any monitoring method, one always wants to have, from qualitative until quantitative, sufficient necessary conditions. However, for underground microseismic monitoring, such sufficient conditions are difficult to propose. Compared with stealth aircraft and navigators, microseismic monitoring and inspection are more difficult; there exists fluid separation over there, and targets and distances can always be set for comparison; and here is solid separation. Specifically:

1. Due to the microseismic characteristics, that is, tiny and shear rupture being dominant [1-3], the monitoring of them is very different from the general natural and artificial earthquakes. For example, for the main magnitude range M∈ [-3, -2.5] of fracturing-induced microseismics, often a few hundred meters away, useful microseismic signals are confused or submerged in noise. In addition, the shear rupture mechanism radiates both longitudinal wave(P) and

Corresponding author: Beiyuan Liang, Ph.D., senior scientist, research field: microseismology.

transverse wave (S) outward, and the initial polarity (±sign) of their propagation is different when reaching seismic stations in different directions [4, 5]. Simply observing from the signal records, there are no any microseismic information such as presence, event amount, arrival amplitude and polarity.

2. Microseismic monitoring such as fracturing is to invert for the underground spatial and temporal distribution of microseismic hypocenters or their released energy by processing observation signals, that is, the SRV (Stimulated Rock Volume), and its corresponding correlation with life, production, and the geological and physical properties of rock. For example, the "high energy" display of a certain time and space may be microseismic, or caused by the station records with the imperceptible noise pollution at the same time; the inversion result is generally not unique.

However, necessary conditions are also quite strict constraints; if a certain necessary condition is violated, the monitoring will inevitably fail, or at least its reliability should be strongly questioned. The process of developing microseismic VS shows that when there are enough necessary conditions, the monitoring is guaranteed in a higher probability sense [1-3].

In order to propose the necessary conditions for the reliability of microseismic monitoring, as a researcher, and developer, or applicant, we have the following principles and practices [1-3]:

1. Obeying the characteristics of microseismic as monitoring target, and corresponding monitoring, and strictly abiding by the principles of seismology and signal processing;

2. It is generally impossible to copy the specific methods of monitoring naturally small and artificial exploration earthquakes, but should implement a large number of quantitative experiments, and develop new software and hardware;

3. Using forward methods of artificial microseismic, background random noise, engineering geological models, and other data that are close to actual conditions to study and confirm the correctness of data stacking and denoising. For example, we set up artificial data with a signal-to-noise ratio (S/N) of about a few percent to verify the feasibility of the VS principle [6].

4. Using different microseismic monitoring methods, such as the outputs of VS and BPM (Borehole Proximity Monitoring) that are close to the hypocenters and meet seismic requirements, to compare with each other [2].

5. The spatiotemporal distribution of the final output of microseismic released energy should statistically conform to known principles and observation rules of seismology, rock mechanics, and tectonic geology [2], and are not inconsistent with production data.

In Chapter 2 first, based on the above qualitative principles and practices, a detailed summary is provided to R&D (Research and Development) and applications for a clear quantitative, at least semi-quantitative necessary condition for judging the reliability of VS microseismic monitoring. To illustrate the above 5th principle, the spatial and temporal distribution characteristics of various microseismic energy obtained based on these conditions are then summarized. In Chapter 3, fracturing monitoring of the platform A with coalbed methane wells is mainly used, and other examples are supplemented, to illustrate the reliability verification of VS applications. If something exists in document [1], except for important formulas and conclusions, this article only cites the specific chapters and figure numbers in Ref. [1].

As VS ground monitoring gradually overcomes technical difficulties, and conducts detailed research on various monitoring methods, the data migration and stacking based on low S/N and shear mechanism, as well as the technology of joint inversion correction of traditional locations and velocity model used in the early stage of VS research and development [7, 8] (also used in general seismology), is becoming increasingly important [1-3]. This paper proposes suggestions for the development of microseismic monitoring in Chapter 4, including the improvement of various monitoring methods, as well as many fields that can be applied. This will establish a solid foundation and complete seismic measurement methods for microseismology. Finally, Chapter 5 is the conclusion.

2. VS Principle, Application Necessary Conditions, and Distribution of Microseismic Energy

2.1 Microseismic Characteristics and Current Situation of Microseismic Monitoring

Table 1 of Ref. [1] lists the two microseismic characteristics: tiny and shear as main rupture style, so its most important monitoring characteristics are data processing of mathematical statistical concepts guided by low S/N, focal mechanism of shear dislocation, mainly using S wave with larger amplitude. Accordingly, and to the requirements of seismometry [4, 5, 9], Tables 2 and 3 of Ref. [1] list the advantages and limitations of different monitoring methods, the technical reasons for their limitations or defects, and further development suggestions. For detailed suggestions on development prospects, including the application improvement of some specific areas or methods, see Chapter 4.

The author just attended two international conferences [10, 11]. Looking at the conference speeches and posters on microseismic monitoring, there is no exceeding the scope of comments in Ref. [1]. It is only necessary to further emphasize whether there is a full understanding of microseismics and their monitoring characteristics should be the main reason for the stagnation of microseismic monitoring.

2.2 VS Principle

The principle of VS is briefly described as: based on the low S/N and focal mechanism of shear dislocation, VS combines all possible polarities of arrivals recorded in each station within a certain period of time, implements large-scale vector migration and stacking of certain waveforms, and selects a distribution with higher released energy from all trials in the sense of probability. The equation of the principle is:

$$E_p = r(P) - r_{\min} = \left(\frac{\frac{1}{M}\sum_{j=1}^{L}\left(\sum_{i=1}^{M} x_{ij}\right)^2}{\sum_{j=1}^{L}\sum_{i=1}^{M} x_{ij}^2} \right) - r_{\min} < S/N = \frac{\sum_{j=1}^{L}\sum_{i=1}^{M} s_{ij}^2}{\sum_{j=1}^{L}\sum_{i=1}^{M} n_{ij}^2} \tag{1}$$

See the specific explanation of Eq. (1) in Ref. [1]. The E_P defined here at the point P in space is the microseismic released energy, and the correlation coefficient *r* of all stations, and also the minimum S/N. The spatiotemporal distribution of E_P can be obtained from Eq. (1) and then the SRV can be defined; the minimum S/N means the reliability of monitoring.

2.3 Necessary Conditions to Ensure the Highly Likely Reliability of VS Applications

According to the principle, the requirements for improving S/N, as well as our applications, VS proposed the necessary conditions for the successful microseismic ground monitoring, that is, the microseismic monitoring characteristics, or the indispensable key points for identifying and checking the reliability of VS application (Table 4 of Ref. [1]):

1. Using geophones with lower natural frequency suitable for monitoring microseismic, such as ~5Hz. It has a spiral shell that can be screwed into the ground and maintained highly coupled to the earth.
2. Each station of the seismic network should be in a quantitatively determined quiet location, with discrete horizontal distribution covering the monitoring domain.
3. The data stacking must take into account the shear mechanism. Generally, P wave with much smaller amplitude is abandoned, and S waves, namely Sh and Sv waves with much greater energy to reach farther places, should be used.
4. The data stacking should use a minimum number of stations greater than or equal to a statistically significant $N_{\min}$ ($\geq 10 \pm 2$). The seismic network should contain the number of stations with a total of $\geq 2 \times N_{\min}$.
5. Effective denoising, especially the interferences from natural earthquakes and ground machines.
6. The lower limit of S/N (or release energy, or the correlation between stations) output by the stacking

should ≥~1%, which is the threshold of existing microseismic (statistical comparison through applications).

7. Using characteristic parameters with quantitative ranges to remove noise-coherent interference, then obtaining microseismic released energy E_P, or SRV(t) with respect to time.

8. Accumulating all SRV(t) to define and judge the spatial distribution of SRV of the target domain in a probabilistic and statistical sense.

The conditions 7 and 8 above define the process of obtaining SRV. From the large number of VS outputs of data stacking, it was found that due to the tiny microseismic, the noise interference that our programs are not easy to detect will continue during the entire monitoring process. This period of time when there is the suspected interference must be discarded [9]. For example:

1. As long as effectively denoising, the background noise recording is random or near random, but it is also possible to output a very small number of “high energy” points. The noise interference is that it has a small number of points and a very low probability of occurrence;

2. “High energy” is connected in pieces and strips to the scanning boundary with the order of kilometers (how far the overflow boundary is unknown), or the area occupied by this “high energy” is unreasonably large, such as thousands of square meters; after comparison of field sites, it is related to the noise pollution of large-area stations of S/N < 1 that cannot be identified by programs such as remote earthquakes and/or heavy vehicles.

The above conditions are confirmed based on seismology and a large number of experiments. Some are statistical, some are strict but can be achieved, and some are tried to expand S/N requirements according to the principle. These conditions can be further quantitatively refined to specific numerical values. Based on the conditions, a quality inspection system for data acquisition, seismic network, and data processing and interpretation has been established.

2.4 Spatial-Temporal Distribution of Microseismic Released Energy Monitored by VS

If the reliability of R&D and application is guaranteed with a high probability and the accuracy range of VS is properly considered [1-3], the spatial and temporal distribution of the released energy or SRV morphology can be studied and described; its characteristics should conform to the principles or observation laws of known rock mechanics, tectonic geology, or to microseismics and its monitoring characteristics [1], and must also be consistent with production data. Microseismic released energy in space and time (see the next chapter for details) may be:

1. The statistical observation characteristics are [1-3, 9, 12-19]:

- Intermittent changes with time. The time required for the accumulation of energy in a region to begin rupture is shorter and will gradually extend later; because as the volume or filter loss of the fracture net gradually increases, the energy of the new microseismic group will be accumulated for a longer time.
- Jumping with space changes. The area and scope of each microseismic group is mostly part of the final fracturing network, such as one branch or its part, until the final larger and dense SRV is formed. Most microseismicities are increasing the density of fracture network, or “filling in the blanks”; this is the random jump in space. The jumping ability is also manifested in that a rupture somewhere induces a distant microseismic group, and in the end these groups may or may not have ruptures connected to the final network. There is almost no the SRV to be formed from near to far gradually.
- The final space effect for a certain period is “the flowers scattered by goddess, but appropriately concentrated.” There are very few phenomena of clean only one crack, or a single fracture area, or perfect symmetry along the horizontal well trajectory. Even

very small microseismicity can induce distant large fractures; if the explanation for this activity is not isolated from far places, it is impossible to distinguish the microseismicity at the target.

• SRV morphology. It should conform to the observation laws of raptures in tectonic geology and rock mechanics [20], as well as the characteristics of focal mechanism in seismology [4, 5].

2. Corresponding production accidents or measure effects. For examples:

• Comparison of SRVs resulting from the more than two times fracturing; The latter is generally always more or less increasing the network density and/or extended the network range on the basis of the previous one; unless the pressure or displacement is significantly reduced, or the fracturing input energy is less than the filtration energy lost due to the density increase and range expansion of the SRV.

• The injection fluid is sprayed near the fracturing well due to the SRV connection to another well; and the fracturing of the coal mine roof extends to the tunnel so that water leaking happens.

• The fault zone effect. That is, for small microseismics, the propagation of stress concentrations at the tip of the crack is limited by the soft zone [2].

• The average equivalent microseismic magnitude corresponding to different conditions should be within a certain range [2].

Some of the above judgment conditions may not be unique and do not become strict necessary conditions, but the general statistical results in space and time should be in line with the focal mechanism of shear dislocation and general observation or experiment of tectonic geology, and be consistent with the known production data.

3. Inspection Examples

The whole process of VS application is tested, including the steps of data acquisition, denoising, stacking and interpretation, by using the necessary conditions for reliability, based on the microseismic monitoring of coalbed methane fracturing on platform A with 6 wells, supplemented by other existing monitoring examples.

From August to September 2024, hydraulic fracturing was carried out in each coalbed methane well on platform A. The overall reservoir depth is about 2,030m, and the reservoir thickness is 8-11m. Platform A contains 4 directional wells (D1-D4) and 2 horizontal wells (H1, H2); Each horizontal well has 12 fracturing stages, and each directional well is a layer of fracturing.

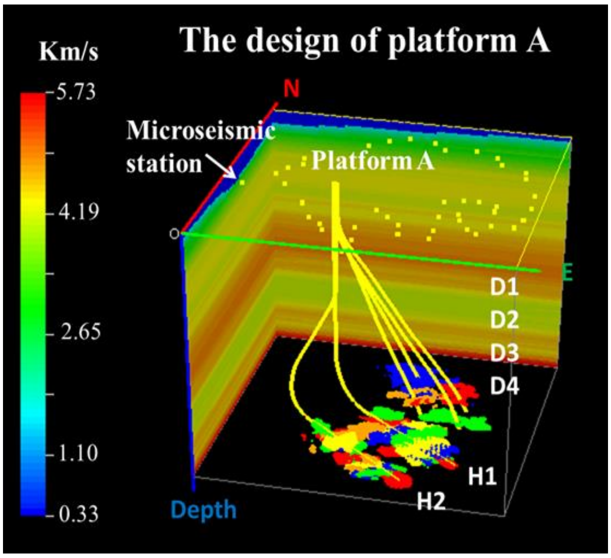

Fig. 1 Fracturing design of platform A.
The two planes in the background are the two profiles of the 3D velocity model interpolated based on the logging data, from which the ruggedness of the mountainous surface can be seen. The left part of the figure is the color scale of the velocities(km/s). The high energy distribution induced by fracturing of each stage is in a coal seam with a thickness of 8-11 m. The energy distribution of different stages uses different colors to distinguish them. The monitoring area of each stage is a cube with a plane area of 1,000m× 1,000m (not drawn) around the center of the perforation section with up and down 100 m, respectively. The yellow line is the well trajectory, and the yellow color point is the seismic station; Among them, specially monitoring the several inclined wells and two horizontal wells as different groups, the network moves from northwest to southwest, and some stations coincide, and the monitoring network maintains 25-27 units for each group, covering the monitoring area in a plane. The sequence of fracturing stages and high-energy colors of horizontal wells: 1—red, 2—green, 3—blue, 4—yellow, 5—orange, and then repeat the cycle. The sequence of the inclined wells is arranged from right to left in D1, D2, D3, and D4, respectively.

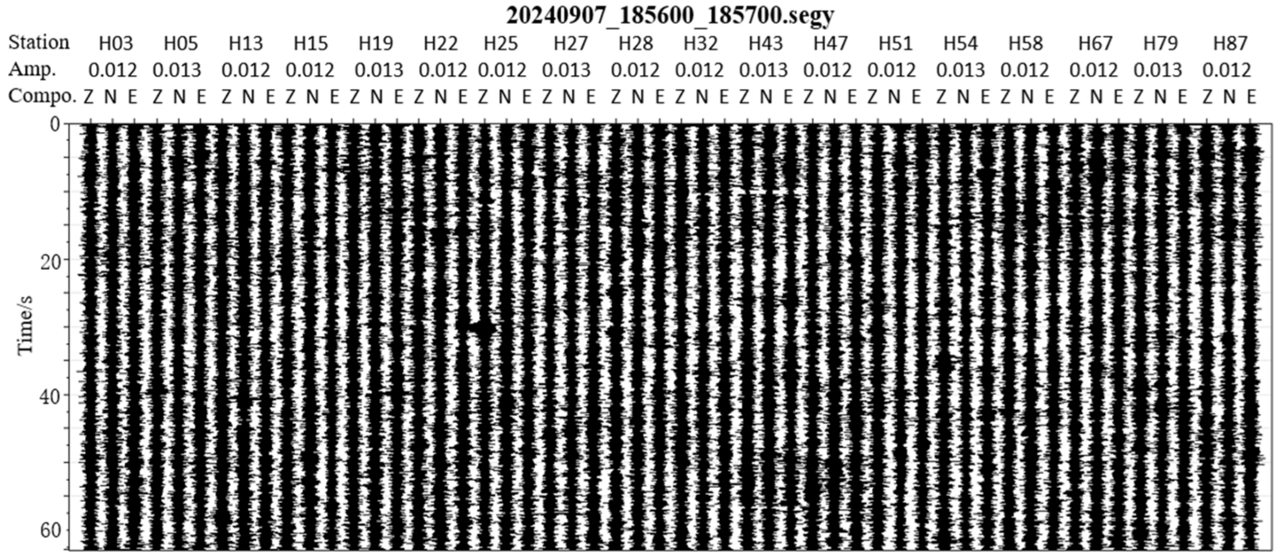

Fig. 2 Time period recording after denoising and amplitude compensation.
The title shows the recorded period from 18:56:00 to 57:00 on September 7, 2024. The horizontal axis is marked with the microseismic station name, average amplitude, and components (ZNE corresponds to depth, north, and east).

Directional well D3 fractured in-situ four times. The in-situ pump shutdown was implemented in 7 stage times of horizontal wells and 4 layer times of directional wells; Two of them were added temporary blocking balls during the pump shutdown.

3.1 Data Acquisition and Denoising

The overall fracturing design is shown in Fig. 1. According to the distribution of fracturing stages/layers in several wells on platform A, two monitoring networks were designed respectively, and two batches of quiet point field surveys were carried out, and a total of 64 points were measured. Choosing the values with lower background noise, and 25-27 units per network were deployed; The quality of all stations is excellent [21]. Although it is in a mountainous area, the geometry of each station network is qualified. The data after denoising [22] showed that the data before stacking were in a random or near-random state (Fig. 2), which was of good quality. Data met the requirements of conditions 1-5 in Section 2.3.

3.2 Data Stacking and Definition of SRV Morphology

The minimum average number of stations in migration and stacking is 16.8, the maximum is 22, and the average number is 19.2, which meets the requirements. The stacking uses the S-wave vector of each station, that is Sh and Sv, the two independent propagation components. Taking well D4 as an example, according to the necessary conditions 6 and 7, after removing the periods (min) with suspicion of noise interference (necessary condition 7), 34 periods (including the two wave types of Sh and Sv in one period) that meet the minimum S/N, that is, the higher microseismic released energy, or correlation magnitude, are selected as the important periods, see Fig. 1 on the left in Ref. [1]. At the same time, VS accumulates arithmetically and averagely all the important periods until the current time; these accumulations are called the change of SRV over time, which is shown in the right column of Fig. 1 in Ref. [1]. Fig. 1 of Ref. [1] shows the jumping and intermittent distribution of microseismic released energy during fracturing, also in Ref. [9, 12-19].

After fracturing, the accumulation corresponding to the last important period is just the spatial geometry of the SRV in the probabilistic and statistical sense, defined by necessary condition 8. The final total effect is “the flowers scattered by goddess, but appropriately concentrated (around the fracturing stage, i.e., Fig. 2ab in [1])”.

3.3 SRV Morphology and Equivalent Microseismic Focal Mechanism

In recent years, with the continuous improvement of the necessary conditions for VS application, the specific spatial shape of SRV in each fracturing stage has become clearer. After statistically counting the 497 fracturing stages monitored by VS, including the 31 of platform A, the following preliminary conclusions are made [2]:

1. Vertical distribution of SRV. Despite the vertical error of a hundred of meters [2,3], the SRV accumulation in VS applications, and BPM longitudinal distribution statistics, one can question or hypothesize that for fracturing-induced microseismic in horizontal stratified structures, SRV is mainly extended within the reservoir. After carefully screening nearly 100 BPM reports, 9 relatively reliable cases were found, which both published and could reliably judge the vertical distribution of the hypocenters; If SRV is defined here as a dense hypocenter group, its distribution is basically consistent with the reservoir height. Therefore, for the fracturing-induced microseismics in the stratified structure, and the reservoir thickness is much smaller than the length of the SRV, the SRV mainly extends horizontally in the reservoir, and the reservoir thickness can be used to represent the SRV height. The most important mechanisms in tectonic geology and rock mechanics for this may be:

• The maximum tectonic principal compressive stress (σ_1) in the continental region is horizontal or near horizontal [20]. At this time, fracturing and other induced ruptures are easy to spread horizontally;

• Structural distribution of bedding folds. The layered structure with different strengths is prone to the formation of interlayer slip fragmentation thin layers, which is the vertical buffer boundary encountered at the stress concentration front of fracturing microseismics.

2. The final horizontal morphology of SRV is the X-type of “Anderson discussion” [20] (Fig. 2ac in Ref. [1] and Fig. 3 in Ref. [1]), or a part of the X (Y, V, I, etc.). Or the internal morphology of the conjugated shear zones is shown in the form of flying geese (Fig. 2a in Ref. [1], Fig. 3b in Ref. [1]). These patterns may often appear before the end of fracturing. This X-type uses its acute angle to correspond to the azimuth of σ_1, which is the microseismic equivalent source mechanism.

These morphologies are in line with the observation and model of the tectonic geology dominated by shear fracture [20]and the focal mechanism in seismology of passive earthquakes [4, 5].

3.4 Microseismic Magnitude Range

Based on the table of previous statistics for microseismic magnitude [22], Table 1 adds the magnitude statistics of fracturing of coalbed methane on platform A and ultra-deep wells [19]. Coal methane is generally much less strong than those of its roof and floor [18], and can be regarded as fault zones, so the energy released by fracturing-induced microseisms is also small. The reservoir depth of ultra-deep wells is large, and the fracturing pressure is also large. The equivalent magnitude of microseisms in various rock bodies is within a reasonable range.

Table 1 Equivalent Richter magnitudes of some microseismic styles.

Induced microseismic styles	Average energy (J/s/station)	Equivalent average magnitude (M)
The collapsed goaf of the coal mine	2,670	-0.9
The collapsed goaf of the coal mine (roof fractured)	1,380	-1.1
Oil well injection with 70 ℃ hot water pretreatment (surrounding rock with 30 ℃)	18	-1.8
Fracturing of ultra-deep oil wells (6.5-6.7 km)	19	-2.4
Coal mine roof fracturing	13	-2.5
General oil well fracturing	10	-2.8
Fracturing of coalbed methane (platform A)	3	-3.1

3.5 SRV Characteristics of ≥ 2 in Situ Fracturing

Fig. 3 shows the 2D distribution of SRV monitored by four rounds of in-situ fracturing microseismic monitoring for well D3. With small change in pressure and displacement, each fracturing SRV expands its boundary on the original basis, and further increases crack density in it. However, by the fourth time, it is obvious that the total injection and total filtration energy are close to each other, and only some of raptures in it occur. It is impossible to continue to expand the geometric boundaries of SRV without significantly increasing the injected energy. Fig. 4 shows the secondary in-situ fracturing effect of the G1 well. These phenomena are in line with the principle of conservation of energy.

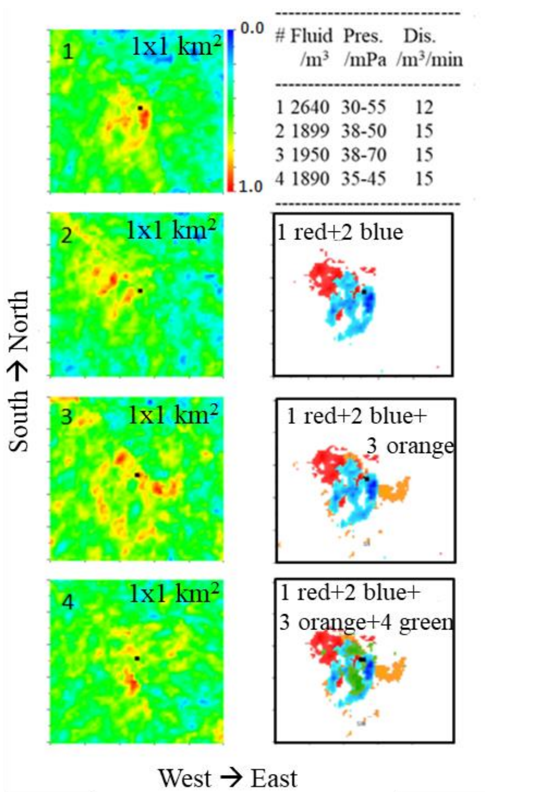

Fig. 3 SRV changes of in situ 4 times fracturing for well D3. The left column shows the 2D energy distribution of each of the four rounds, and the right column shows the cumulative SRV effect of each cycle. The black spot in the center is the middle of the fracturing perforation section; The range of 2D is 1,000m×1,000m. The color scale on the right side of round 1 is for the graphics of these 4 rounds. In the three figures on the right, red, blue, orange, and green represent the SRV of the 1st, 2nd, 3rd, and 4th rounds, respectively. The injection fluid, pressure, and displacement for fracturing are listed at the right up corner.

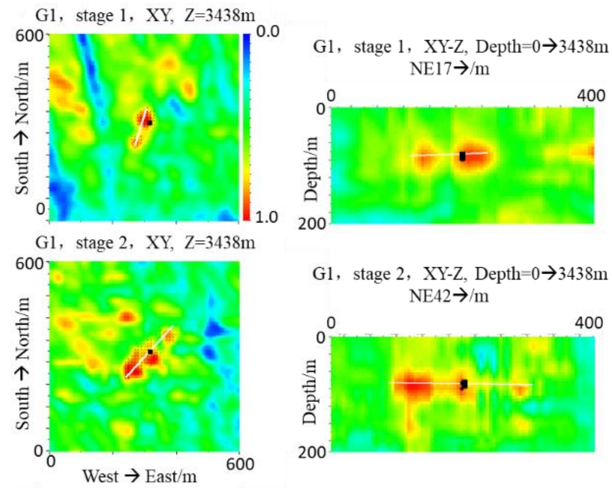

Fig. 4 SRV changes of in situ 2 times fracturing for well G1. The upper and lower rows are the SRV distributions of the first and second fracturing, respectively. The left column is the 2D plane, and the right column is the 2D longitudinal section. The white lines are the direction or tendency of the SRV. The central black spot is the center of the fracturing perforation segment. The color scale on the right side of the left picture in the upper row is suitable for the common use of these four figures. Note that the longitudinal profile here shows that most of the large vertical errors near the reservoir are offset.

3.6 The Effect of In-Situ Pump Shutdown and Temporary Plugging

Pump shutdown in situ or actually ≥ 2 times fracturing, and/or temporary plugging (PS) during fracturing is to create more cracks in new directions (Changed Direction, CD=during fracturing, it unfolds in both sides relative to the horizontal well trace) or location (Extended and/or crack density Increased, EI) on top of the existing SRV. The “in situ” here refers that the length of the fracturing stage is tens of meters.

Qualified SRV can be: full length ≥ 200 m, equivalent width ≥ perforation section length, and the ratio of the length or area of the two wings ≥1/3. Among the 497 stages counted, 34 (7%) SRVs were unsatisfactory (close to or on one side of a well trace), and 463 were qualified; Almost all of fracturing has sufficient EI whenever CD is qualified.

Seen from Table 2 [2], it is clear that the effect of CD in fracturing is independent of the in-situ PS. After careful observation, the final fracturing effect is not

Table 2 Statistics of pump shutdown effect [2] for463 (100%) qualified SRVs.

59% use PS, thereinto	86% CD before PS 14% CD after PS
41% use no PS, thereinto	90% CD in the 1st half of fracturing 10% CD in the 2nd half of fracturing

necessarily related to the perforation mode, reservoir type, and other spatiotemporal factors.

Why is in-situ PS invalid? Perhaps even if there is a new crack, it is easy to quickly connect with the original SRV. In terms of mechanism, this kind of PS and restart is no different from the ≥ 2 times in situ fracturing. As for the stress concentration or the trend of further development of fractures in the existing SRV, whether it is "fill-in-the-blank" or expansion in some directions, it should be determined by the distribution of fracture density within the existing SRV, the degree of fracture in all directions, the filtration rate of existing raptures in the rock, and the displacement and total amount of continuous or re-injection. For example, if one side of the well trajectory has a large degree of rupture, it means that it is more filtered and it is difficult to achieve the stress concentration degree of further rupture, while the other side is easier; At this point, rupture steering expansion occurs. This is not necessarily related to whether to stop the pump and start it again.

What is the effect of PS and other measures on large-scale fracturing stages, such as more than a couple of hundred meters? There are too few existing examples, and there is specially a lack of control between using and not using PS, which needs to be further experimented and calculated.

3.7 Fracturing Injected Fluid Sprayed from Adjacent Well

In VS applications, the fluid injected being ejected from adjacent well occurred twice during fracturing, as shown in Figs. 5 [12] and 6 [13]. This is an excellent constraint to verify the SRV trend output of VS microseismic monitoring, especially the phenomenon in Fig. 6, which was not confirmed by microseismic monitors and oilfield microseismic applicants until the acceptance a few months later.

3.8 Fault Effect

Continuing to pay attention to the SRV strike in Fig. 6, the SRV eastward development is almost here because the eastern part of the fracture point is adjacent to a known fault. The magnitude of fracturing-induced microseismic magnitude is small (Table 1), so it is difficult for these ruptures to cross known faults; In other words, a fault region may be the release zone of the stress concentration on the SRV development or rupture tip of these microseismics. Even if a rapture crosses a fault zone, it may be sharply extinct due to a decrease in stress concentration. This phenomenon has been observed not only in fracturing applications, but also in steam-injected production applications [17].

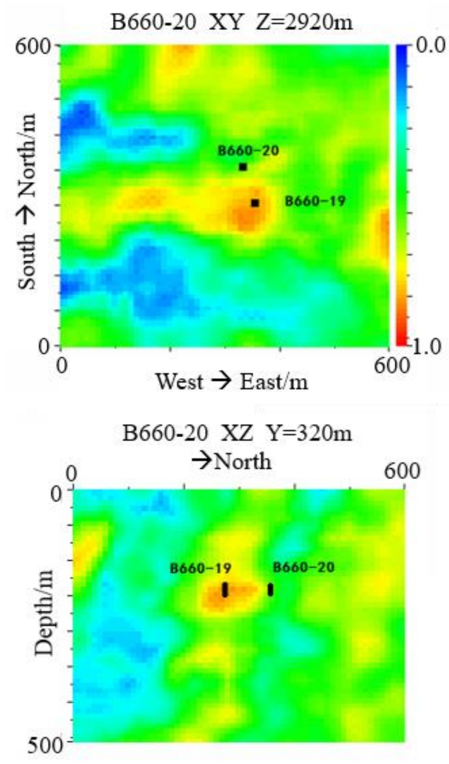

Fig. 5 Microseismic energy distribution in the 2D plane (upper) and 2D profile (lower) of the fracturing monitoring of well 660-20 in Shengli Oilfield.

The black spots mark the projection of the 660-20 and 660-19 reservoirs on the plane. Well 19 ejected fracturing sand and liquid during fracturing in well 20, which was consistent with the SRV direction detected by VS [12].

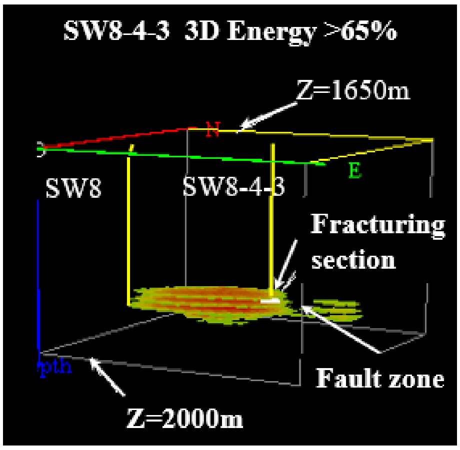

Fig. 6 The 3D microseismic released energy from fracturing monitoring in well SW8-4-3.

The yellow line is the wells SW8 and SW-4-3, the latter being fractured well. The white line is a schematic indication of the fracturing section. The main fracture of the fracturing runs along east and west, with a length > 200 m. Well SW8, which was < 300 m apart, ejected fracturing sand and fluid during fracturing in well SW8-4-3[13].

In fact, even for a weak zone of interlaminar rupture caused by horizontal stratification deformation of different intensities under the action of the maximum horizontal principal compressive stress, it is difficult to cross the zone for SRV with the fracturing microseismic magnitude (Table 1) [2].

4. Suggestions for the Development of Microseismic Monitoring

The basic idea of the improvement and perfection of microseismic monitoring or microseismology includes:

1. Fully understand microseisms and their monitoring characteristics [1];

2. Based on these characteristics, the advantages and disadvantages of each monitoring method are clarified, up to the details of the data acquisition and processing [1];

3. Establish a clear technical route for improvement and development for a method or an application field.

Thus, the complete methods of data acquisition and processing may be established, so that microseismic monitoring can be correctly applied to possible fields.

Ref. [1] has listed and analyzed the main problems and limitations for each type of monitoring method, or data processing method, and some application fields. This chapter lists the fields in which microseismic monitoring can be applied based on its main characteristics and its monitoring characteristics (Table 3), and puts forward several important suggestions for the development of microseismic monitoring, including:

1. The key technologies for the development and perfection of microseismic monitoring.

2. The similar method like VS could be further improved as a cost-effective, ground-based, and conventional or routine microseismic monitoring method.

3. BPM as to be close to the hypocenters despite its high cost can be the best method to study microseismics. However, it is necessary to add joint inversion for traditional relocations and velocity model, and migration and stacking to expand the monitoring scope and improve the monitoring quality.

4. Mine microseismic monitoring can improve the current monitoring level of strong microseismics and small earthquakes (accidents may have occurred at this time) to real microseismics for early securely warning. And

5. Expand the monitoring of small earthquakes as the precursor of destructive earthquakes to microseismics.

Table 3 The scope and significance of microseismic monitoring.

#	Field and significance
1	Fracturing of conventional and unconventional oil and gas, waste storage, etc.
2	Extending the monitoring range and improving the quality of the BPM.
3	Oil and gas access and safety assessment.
4	The leading edge or empty area of the water injection (gas) production process.
5	Mine (roadway, tunnel, etc.) safety warning.
6	Determining the boundaries and internal characteristics of coal incineration areas.
7	Monitoring of cross-border mining.
8	As aids of artificial seismic exploration.
9	General tectonics, stress and strain, and precursor research of destructive earthquakes.

4.1 The Key Technologies for the Development of Microseismic Monitoring

The most important starting point here is the tiny and shear rupture characteristics of microseismics. Therefore, microseismic monitoring should be based on low S/N and shear dislocation focal mechanisms and corresponding necessary conditions (Chapter 2).

On the other hand, because the fineness of microseismic monitoring is much higher than that of natural small earthquakes, the requirement for the precision of the velocity model used for location is also very high. In this regard, in addition to using existing data such as seismic exploration and logging, for dynamically changing or insufficient data of existing velocity models, the joint inversion for traditional relocations and velocity model can be used to promptly correct the locations and velocity values. In fact, in the early development of VS, strong microseismic and small earthquakes were used to carry out the joint inversion as an aid to exploration [7, 8]. The formula and process of this inversion are briefly described below.

The monitoring target domain is divided into a 3D grid with m points; Let the time difference between a seismic event observed by the nth station, t_{On}, and the theoretical calculation based on velocity model, t_{Tn}, is:

$$dt_n = t_{On} - t_{Tn} = t_{On} - \int \frac{dl}{v} \approx t_{On} - \sum \frac{\Delta l}{\bar{v}} \qquad (2)$$

where v is the velocity in any mesh being through by a seismic ray, often set to slowness $1/v$, and l is the path of the mesh. The integration for the path can be completed by ray tracing. The path of a ray is determined by the sum of the product of the slowness and geometric distance passing through each mesh, and if n is large enough, a set of large linear equations can be formed by Eq. (2), dt_n, n=1, 2, 3, ...; The solvable unknowns are the corrected slowness values. The solved new set of slowness values is then sent back to the new velocity model, and the new t_{Tn}...; The above process can be used repeatedly until the d_{Tn} is small enough, and the adjusted seismic wave velocity model and seismic locations (x, y, z, t) can be finally obtained. For traditional relocation, the magnitude, M, can also be obtained, and the equivalent microseismic magnitude is used for low S/N [22].

4.2 Ground Monitoring

Microseismic monitoring methods can be divided into BPM (See the next section) and ground monitoring. Due to the tiny microseisms, VS can only be used as a cost-effective routine means of ground microseismic monitoring. The main data processing method is based on the low S/N and shear dislocation focal mechanism and the corresponding necessary conditions (Chapter 2). The limitation and further improvements of VS are:

1. Although the vertical distribution of fracturing-induced microseismic can be confirmed in reservoirs, the cost of surface monitoring causes a large height error in SRV, and it is difficult to locate microseismic swarms in more complex situations, such as above fracturing layers.

2. The existing data stacking is combined with joint inversion for correcting locations and velocity model to facilitate the acquisition of a more refined velocity model if conditions permit.

3. Further improving the reliability and real-time computation speed of automated processes for data acquisition, processing, denoising, and interpretation.

Others, such as using only P waves, or single vertical components, or equidistant arrangements without considering quantitative quiet point deployment, or attempting to locate deep hypocenters traditionally on or near the surface (such as within a few hundred meters, without knowing that much of the ground interference is transmitted from underground) [1], have to be abandoned.

4.3 Improvement and Perfection of BPM

The main limitations of BPM are the poor coverage of the target region by seismic network, the large traditional location error, and the failure of the location distance out of a few hundred meters [1]. In addition, the domain of the velocity model used includes just the range of the geophone array and the target, so that the microseisms themselves dynamically affect the location quality [1].

However, Section 3.3 illustrates that although more reliable BPM monitoring accounts for only a few percent of the total literature, as long as the laws of seismometry are strictly followed, BPM can be the best way to study microseismicity, albeit costly, because it is close to the hypocenters. If BPM is improved, the monitoring scope is expanded, and the observation quality is improved, microseismic monitoring may form two powerful monitoring methods: one is the routine means of ground microseismic monitoring that can accompany production, such as VS; The second is the BPM of the best microseismicity research method close to the hypocenters despite the high cost. Therefore, this section puts forward the following suggestions for improving BPM:

1. There should be ≥ 2 monitoring wells, unless the monitoring boundary is < 200m away from the detector array; and the detector array better spans the reservoir vertically;

2. BPM should point that the traditional location using the initial arrival of the record is only valid for a few hundred meters from the geophone array; Otherwise, migration and stacking like VS can be used to expand the monitoring range. And

3. The joint inversion for relocations and velocity model can be continuously combined to correct the large changes in the medium when fracturing.

Here, except for meeting the above condition (1), the focus is on using traditional positioning combined with data migration and stacking. The former is mainly used for the joint inversion for correcting locations and velocity model, and should be converted into energy distribution, which is mutually confirmed with the energy distribution output of the data stacking.

This paper predicts that the SRV expressed by the energy distribution (correlation coefficient among the stations, also the minimum S/N) of the final output of BPM should be shown as a similar conclusion for VS morphology (Section 3.3), as it is consistent with the shear focal mechanism, stress-strain relationship, and general observations of tectonic geology.

4.4 Safety Warning in Mining Areas

In the field of safety warning in mining areas (or underground roadways and tunnels), much so-called microseismic monitoring, similar to BPM, is basically the traditional relocation using seismic waves when they arrive [23, 24], or try to track unreliable or even impossible initial arrivals using P waves with much smaller amplitudes [25];Instead, we should change the R&D idea, count a large number of records, extract the characteristics of microseisms, and raise the early warning of strong microearthquakes and small earthquakes (such as $M \geq -1$, at which time accidents may occur) to the level of real microseismics ($M \geq -3$).

Therefore, the development suggestion here is similar to that for BPM, that is, the first is to develop the data migration and stacking based on the low S/N and shear dislocation focal mechanism, so that microseismic monitoring in the mining area becomes a reality. In this regard, Refs. [26, 27] have paved the way for many problems in mining areas, such as the danger zone of natural collapse of goafs, the determination of the boundaries and internal characteristics of the burning area, and the identification of cross-boundary mining, which can be included in early warning.

In fact, the microseismic monitoring conditions in mining area are much better than those in oil and gas field. First, most of the reservoirs in the mining area are shallow, mostly within 1 km, and currently up to 2 km, which makes it possible to use both P and S waves in most of cases [26]. It is also facilitated to obtain subsurface velocity distributions using joint inversions (Section 4.1). Secondly, there are a large number of roadways in the mining area that can be utilized, which allows the monitoring network to cover the microseismic zone from 3D, which is conducive to improving the monitoring accuracy. From the perspective of practical observation, the development of the network function of synchronous timing of all seismic stations on the ground and underground is the key technology for real-time monitoring and early warning.

4.5 Monitoring Precursor of Destructive Natural Earthquakes

Many explorers of the precursors of destructive natural (or large) earthquakes only count and publish the examples with some precursor observed for large earthquakes, and analyze the laws and possible mechanisms. There are no statistics on those without precursors, and there is no unified analysis. There are many examples of this lack of statistical significance, such as small seismicity and electromagnetic anomalies before large earthquakes, and only about 10% of the statistics with precursor correlation at professional conferences [10].

What is the actual situation of the so-called "no precursor"? Is it that the gestational process of some large earthquakes does not have such a significant observable precursor? Or are there such precursors when in fact current observations or statistics are difficult? For each category of precursors, it seems that the future R&D technical route should be determined by combining numerical and rock experimentally modelling, examples of the presence or absence of precursors with and without all the observations that can be counted in the world, and the mechanism analysis of general mathematical mechanics. Therefore, we suggest:

1. Using the existing natural seismic monitoring network, the monitoring of small seismicity before large earthquakes may be expanded to microseismicity; The migration and stacking may be used to study the small and microseismic activity before large earthquakes.

2. Since ultra-deep (e.g., ≥ 6,500 m [19]) wells have become more common, a geophone array at a depth of more than 6 or even 10 km can be set up to reduce the vertical error of the hypocenters of large earthquakes and their precursors.

From the statistical relationship of the number of large and small earthquakes, rock mechanics experiments, mechanical numerical modelling, and flaw detection before fatigue damage in engineering, there should be at least a large number of microseismicities in a certain range near the hypocenter of a large earthquake, at least relatively strong microseismics (such as $M \geq -1.0$ or 0.0) that is likely to be observed.

At present, the small earthquakes monitored before the large earthquakes refer to the magnitude $M \geq 1.0$ [10], with a monitoring horizontal range of about several to tens of kilometers and a depth of about ten kilometers. Based on Table 1 and application examples of microseismic monitoring, the general summary is that VS can extend the monitoring range of traditional microseismic (M = [-3, -2.5]) location from hundreds of meters to thousands of meters using data stacking [1]. It is expected that after R&D, confirmation and improvement, there may be at least considerable changes in the observation range of small and microseismic activities before a large earthquake, including the magnitude and observation distance, such as reaching $M \geq -1.0$, and the horizontal and vertical ranges reaching tens or a hundred of kilometers or more than the earth's crust, respectively.

5. Conclusions

5.1 The Status of Microseismic Monitoring

The microseismic characteristics are mainly tiny and shear rupture, so its most important monitoring characteristics are based on low S/N, using relatively larger amplitude S-wave as the main wave style, and data processing with the mathematical statistical concept guided by the focal mechanism of shear dislocation. Thus, the advantages and limitations of various monitoring methods, the technical reasons for their limitations or shortcomings, and the suggestions for further development of each method and field can be analyzed [1].

5.2 The Test of Microseismic Monitoring

It is difficult to give sufficient conditions to test the reliability of microseismic monitoring. Often a few hundred meters away, the microseismic signal emitted by a hypocenter is submerged in the background noise, and the traditional location fails. The microseismic energy distribution is not unique in principle to invert for the distribution by data stacking. However, based on the characteristics of microseismic monitoring, forward and inversion modelling, and a large number of experiments, many necessary conditions can be put forward to ensure reliable monitoring with a high probability. VS ground monitoring puts forward eight necessary conditions for verifying reliability. This makes that VS monitors the fracturing-induced effective connecting network (SRV) with the characteristics of shear zones under the action of tectonic stress fields, which are in line with the seismological and geological observations and are closely related to the production data.

5.3 Prospects and Development Suggestions

VS uses the data migration and stacking suitable for low S/N and shear mechanism, and the joint inversion for modifying traditional locations and velocity model, which greatly improves the monitoring distance and quality. Applying the technology may improve the microseismic measurement methods, broaden the application fields, and establish a solid foundation and complete methods in seismometry for microseismology.

References

[1] Liang, B. Y., Jiang, W., and Li, Y.2025. "Ground Monitoring of Microseismic Based on Low Signal-to-Noise Ratio." *American Journal of Energy Engineering* 13 (3): 107-17. doi.org/10.11648/j.ajee.20251303.12.

[2] Liang, B. Y. 2025. "SRV, Focal Mechanism, and Effect of Pump Shutdown of Microseismic Ground Monitoring." In *Proceedings of the International Meeting for Applied Geoscience & Energy (IMAGE 2025), Hydraulically-induced Fracture Network Monitoring*, Houston (IPS 1), USA.

[3] Liang, B. Y., Chang, L., Fang, D. Z., et al. 2023. "Microseismic and Its Monitoring—Toward Vector Scanning of Microseismic Based on Lower Signal to Noise Ratio." *Progress in Geophysics* 38 (1): 47-75.doi:10.6038/pg2023GG0150.

[4] Aki, K., and Richards, P.G. 1980. *Quantitative Seismology: Theory and Methods*. New York: W. H. Freeman and Company.

[5] Bullen, K.E., and Bolt, B. 1985. *An Introduction to the Theory of Seismology* (4th ed.). Cambridge: Cambridge University Press.

[6] Liang, B., and Leng, C. 2016. "Development of Vector Scanning for Microseismic." *Progress in Geophysics* 31 (4): 1620-7. doi:10.6038/pg20160428.

[7] Duncan, P. 2005. "Is There a Future for Passive Seismic?" *First Break* 23 (6): 111-5.

[8] Feng, M., An, M., Wang, X., et al. 2007. "Natural Microseismics in Qinghai's Shizigou Oilfield and Their Geological Significance." *Journal of Geomechanics* 13 (2): 173-8.

[9] Chen, M., Sun, L., Shi, Y., et al. 2025. "Statistics in Vector Scanning for Microseismic." *Science Technology and Engineering* 25 (22): 9273-86. doi:10.12404/j.issn.1671-1815.2404247.

[10] Seismological Society of China. 2025. *Proceedings of the 50th Anniversary of the Haicheng Earthquake and the 2025 Annual Conference of the China Earthquake Prediction Forum*. Beijing: Earthquake Press.

[11] The International Meeting for Applied Geoscience and Energy (IMAGE25). 2025.*SEG and AAPG, Induced and passive seismic (IPS)*. Houston, Texas: IMAGE.

[12] Ma, L., Wang, L., Shen, Y., et al. 2012. *Vector Scanning: Hydro-Fracture Monitoring with Surface Microseismic Data*. Copenhagen, Denmark: SPE-152913.

[13] Ren, Z. C., Zheng, B. T., Ma, S., et al. 2014. *Hydro-Fracture Monitoring Using Vector Scanning with Surface Microseismic Data*. Istanbul, Turkey: AAPG-1948512.

[14] Wu, Z., Lu, J., Shen, C., and Liang, B. 2014. "Data Processing in Vector Scanning." Presented at SEG 1st International Microseismic Technology Workshop.

[15] Zhang, Q., Ren, Z., Zheng, B., et al. 2014. "Hydro-Fracture Monitoring for 86 Stages of Yan227 in Shengli Oil Field, China." Presented at SEG 1st International Microseismic Technology Workshop.

[16] Guo, P., Hu, Z. T., Jia, J. B., et al. 2020. "An Application to the Hydraulic Fracture of Well FT15 by Real-Time Monitoring Using Vector Processing for Microseismic." *Progress in Geophysics* 35 (4):1370-8.

[17] Sang, L., Yang, G., Yu, B., et al. 2021. "Microseismic Monitoring for Steam Cavities of SAGD, Fengcheng Oil

Field." *Progress in Geophysics* 36 (1): 237-49. doi:10.6038/pg2021DD0475.

[18] Zhang, J., Zhao, C., Wang, J., et al. 2021. "MicroseismicMonitoring for Hydraulic Fracture of Coalbeds with Different Dips." *Progress in Geophysics* 36 (3): 1166-75. doi:10.6038/pg2021DD0538.

[19] Wu, G., Cai, J., Zhao, Y. W., et al. 2024. "Ground Monitoring for Fracturing Microseismic of Two Ultra-deep Wells." SEG 1stTarim Ultra-Deep Oil & Gas Exploration Technology Workshop, 2024-UD-06X-OR-080, Korla, China.

[20] Jaeger, J., Cook, N., and Zimmerman, R. 2007. *Fundamentals of Rock Mechanics* (4th ed.). Malden: Blackwell Publishing Ltd.

[21] Liang, B., Leng, C., Xu, L., et al. 2016. "Data Acquisition of Vector Scanning for Microseismic." *Progress in Geophysics* 31 (5): 2333-9. doi: 10.6038/pg20160562.

[22] Feng, Y. J., and Liang, B. Y. 2023. "A Method to Estimate the Microseismic Magnitude Based on Vector Scanning." *Progress in Earthquake Sciences* 53 (3): 115-9. doi:10.19987/j.dzkxjz.2022-072.

[23] Gibowicz, S. J., and Kijko, A. 1994. *An Introduction to Mining Seismology*. New York: Academic Press.

[24] Hu, T., Xu, B., Wang, Y. F., et al. 2023. "Arrival Picking of Mine Microseismic Events Using U-Net." *Science Technology and Engineering* 23 (16): 6802-8.

[25] Feng, Y., Liang, B., and Wang, W. 2022. "Monitoring for Microseismicity Induced by Goaf Collapse at Coal Mine." Presented at EAGE, Near Surface Geoscience Conference & Exhibition 2022, Geophysical Methods in Mining Engineering, Belgrade, Serbia.

[26] Wang, W., Wang, D., and Liang, B. 2025. "Microseismic Monitoring for Roof Deformation in Mining and Early Warning for Safety." Presented at 2025 SEG near-surface geophysical exploration and geo-disaster prevention technology workshop, 2025-NS-07X-OR-020, Chengdu, China.doi.org/10.1190/NSGP2025-030.1.