

Far-Field Microseismic Monitoring—Low Signal-to-Noise Ratio, Wave Vector Extraction, and Equivalent Focal Mechanism

Beiyuan Liang and Jianli Wang

GeoImage LLC, San Francisco, 94118, USA

Abstract: The two important characteristics of microseismic are: tiny, and rupture with mainly shear dislocation mechanism. The monitoring characteristics obtained by the features are: often the signal-to-noise ratio is <1 from a few hundred meters away so that the traditional location fails, one dislocated hypocenter radiates longitudinal and transverse waves into space, and the amplitude and polarity of the waves change with different directions. This is the essence or first principle of microseismic monitoring. Based on previous overview of the current status of microseismic monitoring, this article analyzes the specific reasons why many microseismic monitoring efforts have not made breakthrough progress, and provides corresponding solutions. We can find that many people: (1) adhere to traditional relocation, such as relying on borehole proximity monitoring, or sustain but effectively-limited denoising, but fail to coexist with the residual noise after effective denoising, and implement DMS (data migration and stacking) to discover the microseismic information implied in the noise. (2) Simply use DMS, but the seismic wave vectors are not (correctly) extracted from the 3-component records, based on the far-field displacements generated by the shear force couple at a hypocenter, especially the shear wave vectors SV and SH with large amplitude, slow attenuation, and propagating far distance. And (3) ignore that the wave arrival amplitude and polarity at different receiving places are functions of the coming direction of an earthquake, that is, the focal mechanism of passive or natural earthquakes, the stress-strain constitutive relationship in elastic mechanics, and the Anderson discussion in tectonic geology or rock mechanics, which should be used to guide the whole process of DMS and microseismicity interpretation, and which may be generally called as the equivalent microseismic focal mechanism. These problems are evident in the detections of surface, borehole, mine safety, inversion for velocity models, and small earthquake precursors before destructive earthquakes. This paper takes the research and development of VS (Vector Stacking) as an example, based on the characteristics of far-field microseismic monitoring, to illustrate how to solve the above problems. In order to ensure the reliability of microseismic monitoring with high probability, and the establishment of expert systematic automation, many necessary conditions have to be followed. VS greatly expands the distance range and improves the quality of microseismic monitoring. It can also unify data processing and interpretation of both $S/N > 1$ and <1 using the spatiotemporal distribution of seismically released energy. It has paved the way for microseismologists to develop microseismology, including microseismometry, study the microseismicity, and apply microseismic monitoring in energy field and earthquake forecast.

Key words: Microseismic, microseismometry, signal-to-noise-ratio, vector-processing, focal- mechanism.

1. Introduction

From a seismological perspective, microseismic monitoring is used to study and obtain information about the following within the monitored area: what is the spatiotemporal laws of microseismicity, how the activity is related to production and life events, and how the activity and correlations correspond to known or

possible rock physical, chemical, and geological structural characteristics. Especially in the oil and gas energy field, fracturing, water and gas injection, gas storage construction, and mine safety early warning, etc. are often evaluated through effective microseismic monitoring.

In the past three years, through the improvement and extensive application of our microseismic ground monitoring, Vector Stacking (VS), the comparison of

Corresponding author: Beiyuan Liang, Ph.D., senior scientist, research field: microseismology. E-mail: bjjywd@126.com.

VS with other microseismic methods, and the participation in more than 10 professional conferences, we have summarized the current status of microseismic monitoring, discussed the limitations of various methods and their technical reasons, and studied how to test and develop microseismic monitoring [1-7].

The microseismic magnitude is here defined as (-3, 0), and the corresponding far-field is the distance a few hundred meters away to about hundred kilometers from the hypocenter. In a relatively specific sense, after effectively avoiding and suppressing noise, as long as the recorded signal-to-noise ratio (S/N) is ≤ 1 , it can also be defined as microseismic. At present, the overall development of microseismic monitoring is unsatisfactory, and its technical appearance and main reasons are [1, 2]:

(1) The primary characteristic of microseismics is tiny. That is, in far-field monitoring, the S/N is often < 1 , and the number of events, S/N, polarity and amplitude of the microseismic waveform at the observation point are not known at all. People either continue to try to denoise with limited effect, or approach the hypocenters with poor geometry and cost-effective like BPM (borehole proximate monitoring), or are at a loss what to do, and cannot effectively denoise and then coexist with noise residues, and use the mathematical statistical concept of DMS (data migration and stacking) to process the data.

(2) Even if a DMS is used, the wave vectors cannot be correctly extracted, especially the shear wave (S) vectors SV and SH, which have large amplitudes, slow attenuation, and long propagation, and the DMS alone is often only using the vertical recording instead of accurate longitudinal wave (P).

(3) Because another characteristic of microseismic is the passive seismic nature, that is, it conforms to the focal mechanism dominated by shear dislocation.

However, the focal mechanism is not used to guide DMS, that is, when each wave type reaches different seismic stations, the initial amplitude and direction are different with the orientation of the earthquake.

Such monitoring is unreliable. These problems are obviously present in many detections, i.e. surface, BPM, mine safety warnings, inversion for velocity structure, and precursor monitoring of micro-and-small earthquakes before destructive earthquakes [1, 2].

This paper takes the R&D (research and development) of VS as an example, and explains and demonstrates the follows in the sections: Far-field microseismic monitoring characteristics and DMS, extracting wave vector using far-field displacement from dislocation force couple, data processing and interpretation of microseismicity based on microseismic equivalent focal mechanism, and the necessary conditions to ensure the reliability of far-field microseismic monitoring in the sense of high probability. Finally general conclusions and discussions on the requirements for R&D of microseismology.

We hope that by analyzing the existing problems, technical causes, and solutions in such discussions, we will first reach a consensus on the understanding of the essence of microseismic monitoring, so that the R&D of microseismology, including microseismometry, and its possible applications in various fields will be significantly advanced.

2. Far-Field Microseismic Monitoring Characteristics and DMS

In order to adapt to the general microseismic monitoring, based on the characteristics of microseismic and its monitoring described above, VS uses the following formula to express the microseismic energy release at any point in time and space,

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

The right part of the Eq. (1) is the definition of S/N [8], which squares the useful signal sample point s_{ij} and the noise sample point n_{ij} for a waveform vector, and then sums the samples of M stations and next L samples in a certain time window. The middle of the Eq. (1) is the definition of the correlation coefficient [9], which uses a waveform from all M observation station records, aiming at a space point P , and extracts the correlation coefficient r , $0 \leq r \leq 1$, through the DMS. $x_{ij} = s_{ij} + n_{ij}$, s_{ij} is usually submerged in n_{ij} , and the DMS will reduce the noise and enhance the microseismic signal as commonality existing in many seismic stations. $r_{\min}$ is the minimum value in a space-time interval with little useful signal, and $r(P) - r_{\min}$ means that E_P starts from 0.

E_P is also the lower limit of S/N. If it can be determined, and the true S/N is greater than it, we may judge how reliable the microseismic monitoring is in a period of time. According to the controlled statistics of several thousands of fracturing stages/layers in VS applications, the minimum value of S/N corresponding to the presence of higher microseismic release energy near the fracturing perforation section is $\sim 1\%$, that is, $E_P \geq 1\%$ can be considered as the threshold for microseisms in any certain time and space in VS applications. Except for very specific cases such as strong microseisms ($M \geq -1.5$, possibly $S/N \geq 1$) induced by mine goafs, the S/N found in VS applications is generally $\leq 10\%$.

DMS was early used for exploration seismology [10]. In the VS R&D, x_{ij} is changed from a scalar recorded as a vertical single component to a certain waveform vector of passive microseismic, which are the direct P, SH, and SV waves radiated from hypocenter [11]. The coefficient of the $r(P)$ expression in the middle of Eq. (1) has also been modified to satisfy $0 \leq r \leq 1$ to fit the appropriate interval for understanding S/N [12].

Note that Eq. (1) is also true at $S/N > 1$. In fact, even the traditional relocation will also often interpolate the located circles with magnitude into E_P -like distribution of released energy to better analyze seismicity. In addition, Eq. (1) should be applied after effective

denoising [13], that is, the background noise records should be random or near-random.

3. Extracting Wave Vector Using Far-Field Displacement from Dislocation Force Couple

After data sorting and denoising [13], the next step is to extract the vectors $x_{ij} = s_{ij} + n_{ij}$ in Eq. (1), or to obtain the vibration vectors of direct waves such as P, SV, SH, etc. This requires considering microseismic and its monitoring characteristics, especially the focal mechanism of microseisms in general.

$$\begin{aligned} r' &= (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta), \\ \theta' &= (\cos\theta\cos\varphi, \cos\theta\sin\varphi, -\sin\theta), \\ \varphi' &= (-\sin\varphi, \cos\varphi, 0). \end{aligned} \quad (2)$$

$$\begin{aligned} \mathbf{u}(t) &= \frac{1}{4\pi\rho\alpha^3} \mathbf{A}^P \frac{1}{r} \dot{M}_0 \left(t - \frac{r}{\alpha} \right) \\ &\quad + \frac{1}{4\pi\rho\beta^3} \mathbf{A}^S \frac{1}{r} \dot{M}_0 \left(t - \frac{r}{\beta} \right), \end{aligned} \quad (3)$$

$$\mathbf{A}^P = \sin 2\theta \cos \varphi \mathbf{r}',$$

$$\mathbf{A}^S = \cos 2\theta \cos \varphi \boldsymbol{\theta}' - \cos \theta \sin \varphi \boldsymbol{\varphi}'.$$

3.1 Shear Dislocation Focal Mechanism of Tectonic Earthquakes

The theory of the focal mechanism in seismology [14-19] points out:

(1) Crustal rock volume is generally controlled by the tectonic stress field with 3 principal compressive stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$). The rupture of the rock volume is generally shear dislocation, that is, tectonic earthquakes. The vast majority of earthquakes in the world are tectonic earthquakes which is the fault formation or movement.

(2) After more than 100 years of observation and verification for tectonic earthquakes, the most consistent model of tectonic earthquakes is the elastic rebound theory, that is, tectonic earthquakes are the sudden release of elastic strain energy accumulated at or near fault dislocation.

(3) The focal mechanism of strain energy accumulation and release can be expressed by double pairs of force-coupled point sources acting on the fault dislocation surface (Fig. 1), which is called the shear dislocation focal mechanism.

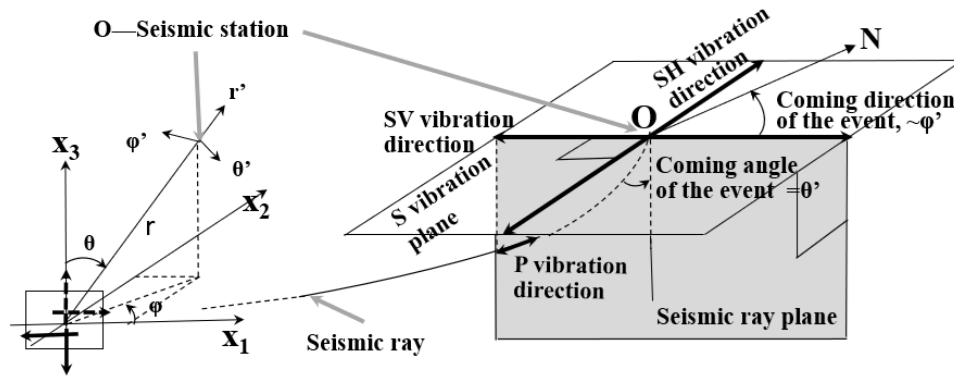


Fig. 1 Schematic diagram of the shear dislocation focal mechanism. The small square at the origin of the X coordinate system in the lower left part means the fault dislocation surface, and the force couple in the horizontal direction (in the X_1 - X_3 plane) acts on both sides of it. The other force couple is orthogonal to the horizontal one. The equivalent spherical coordinate system, $r\theta\phi$, is usually used to describe far-field displacement solutions (Eqs. (2) and (3)). Compared with the $r\theta\phi$ system, the $r'\theta'\phi'$ system can be set up to express the specific P, SV, and SH vibration directions according to the different receiving points and propagation processes. See text also.

(4) Fault zones often appear really as bands with a certain width, containing special forms such as tension and plasticity released by impure shear elasticity (Fig. 2). However, the linear strain energy of the corresponding linear force (simple push or pull) and the shear (or rotational) strain energy of the corresponding torque released by the force couple account for the main components of the mechanical released energy of the faults.

(5) Based on talked above, the far-field displacement solution of the wave propagation (Eqs. (2) and (3), allowed used here from Zhou and Xu [18]) can be derived.

(6) The seismic hypocenter with shear dislocation mechanism radiates P, SV and SH waves into space, and the initial motion characteristics such as push, pull, and shear rotation generated by it remain unchanged from the hypocenter to the far field.

According to Figs. 1 and 3, Eqs. (2) and (3), if $S/N > 1$, the above initial motion characteristics received by each seismic station can be obtained. Eq. (2) expresses the relationship between the spherical coordinate system $r'\theta'\phi'$ and the $r\theta\phi$ used at the hypocenter; the former may be varied by the wave propagation from the hypocenter to each receiving point with different directions. The mechanism of the shear dislocation of the hypocenter can be further deduced from the

distribution of the geometrical states of many stations (Fig. 3). Eq. (3) is the far-field displacement, where the scalar t , ρ , r , α , and β are propagation duration, medium density, ray length, P wave and S wave velocities, respectively. M_0 is the seismic moment of the dislocation surface of the event, $|M_0| = \mu DA$, and μ , D and A are the shear modulus, sliding scale, and dislocation area, respectively.

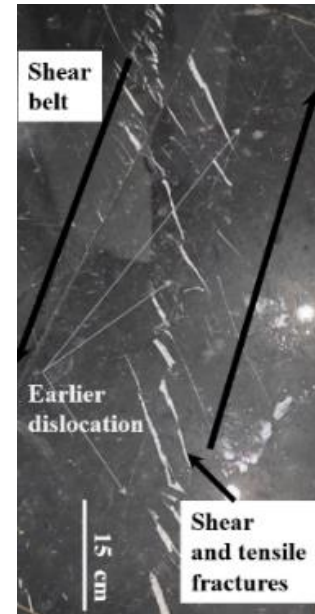


Fig. 2 Characteristics of the shear zone (black shear dislocation arrow pair span the range) in the actual rock sample. 3 fine grey arrows point to an early shear fissure. The white goose flight row is the tension shear happened in the later shear event.

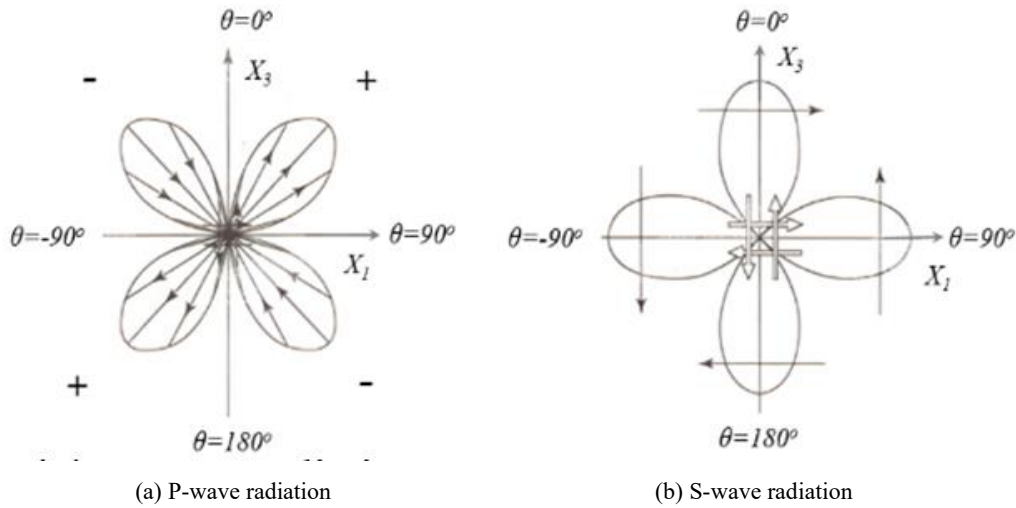


Fig. 3 Wave radiation image in the far-field of force-couple plane (allowed being used here from Zhou and Xu [18]) due to a double force couple at a point (Fig. 1). The length and width of the petal shape indicate the amplitude in different directions. The initial movement of the P wave shows a push-pull diagonal symmetry in different quadrants (indicated by $\pm$ or arrow direction). Those of the S wave are similar, but the large amplitude domain is rotated 45 degrees. The X_1 and X_3 axes are the two conjugate fault trends. You can imagine spatial vibration images by rotating the flat petals in 3D, or use Fig. 1 to first confirm the vibration direction of P, and then imagine the vibration directions of SV and SH.

Obviously, the displacement u at any moment is composed of two parts: r' and $\theta'\phi'$ depending on the velocity of different waveforms and different directions of waveform vibration. In other words, the ray plane where P wave vibration is located is orthogonal to the S wave vibration plane, and S wave is divided into SV wave orthogonal to P wave vibration direction in the ray plane and SH wave orthogonal to SV vibration direction in the S wave vibration plane. SV and SH are two vectors that propagate independently [14].

3.2 Models of Shear Dislocation Faults in Different Fields

The fault shear dislocation mechanism is expressed differently in different fields, but their essence is the same. When there exists a confining pressure and a variable magnitude of the maximum, minimum, and intermediate principal stress ($\sigma_1, \sigma_3, \sigma_2$), the observation model described by Anderson [19] is shown in Fig. 4. In fact, ($\sigma_1, \sigma_3, \sigma_2$) and the corresponding maximum, minimum, and intermediate principal strain ($\epsilon_1, \epsilon_3, \epsilon_2$) are constrained in the acute angle of the conjugate

rupture planes, and only when it is isotropic and there is no pre-fault, they are consistent in orientation and are at half the azimuth of the X-slit acute angle. Fig. 4b shows that regardless of the size of the observation area, if the azimuth of ($\sigma_1, \sigma_3, \sigma_2$), is determined, the resulting diamond-shaped fracture network may vary slightly with the boundary conditions of the stress distribution, such as the fracture line of the actual maximum shear stress line may be bent and branched.

The relationship between stress and strain described in general elastic mechanics shows in a constructive equation, which specifies the all components of stress and strain, including linear stress and strain, as well as shear component (e.g. [19]), all of which are controlled by the boundary conditions ($\sigma_1, \sigma_3, \sigma_2$) in Fig. 4a.

The above-mentioned models of shear dislocation fault mechanisms are not only the basis for each microseismic (or its group) in a short term of data processing, but also show that the macroscopic microseismicity output in space is also very consistent with the characteristics of these models [2, 3].

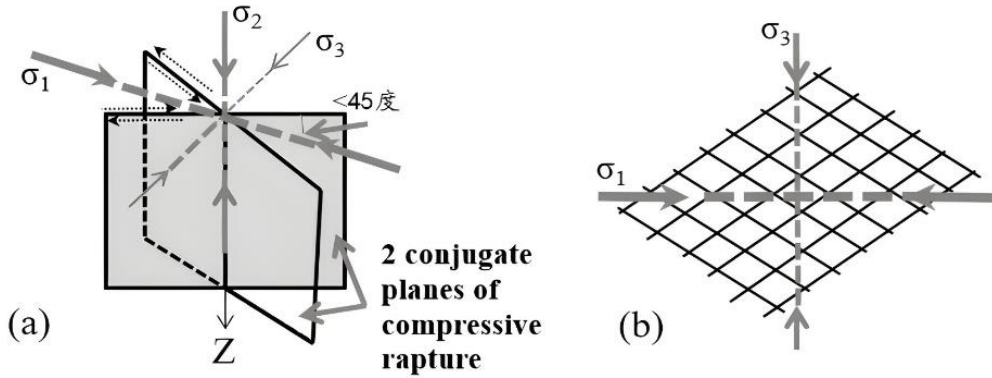


Fig. 4 (a): Schematic relationship between tectonic stress field and shear slip rupture (e.g. Anderson discussion [19]). Commonly known as X-shaped structural rupture. The strike-slip X rupture and tectonic stress field are shown here. The gray arrow pairs represent the direction of the maximum, minimum and intermediate principal compressive stress (σ_1 , σ_3 , σ_2), the two boxes represent the conjugate rupture planes, and the thin black dotted arrow pairs indicate the dislocation slip type of each plane. Rotating this stress field can obtain various normal and reverse faults, etc. (b): Indicates that when a tectonic stress field is given, rock fractures are mostly diamond-shaped fractures, or fractures (fault trends) are often part of this diamond-shaped fracture network.

3.3 Extraction of Direct Waves from Microseismic Far-Field Monitoring

Microseismics are passive earthquakes, which are not only small in strength, but also mainly shear dislocation in rupture style. This is evident from reliable BPM of P and S waveforms with shear dislocation radiation (e.g. [20, 21]). Even in fracturing monitoring, except for the strong tensile characteristics of the near wellbore meter, the formation, connection and propagation of the fracture network during the whole fracturing period are generally shear rupture under the action of the maximum principal compressive stress near the horizontal level in the crust. Therefore, in addition to the explosion or collapse hypocenters, the above-mentioned shear dislocation focal mechanism is also suitable for the rupture mechanism of microseisms.

In far-field microseismic monitoring, just looking at the records, the microseismic information such as the number of microseismic events, S/N, and the initial polarity of the microseismic waveform arriving the station is often unknown, and it is impossible to intuitively judge the vibration direction of each direct wave. However, we can confirm the coming orientation from the space point (if there exists a microseismic over there) to the receiving point in our scanning space, and

calculate the orientation and angle of incidence of the incoming ray trace according to the known velocity model (Fig. 1), so that the vibration direction of P, SV, and SH can be obtained, and the vector value of a certain waveform is projected from the recorded 3-C data.

It is worth noting that any seismic location requires a “known velocity model”, including the necessary known surface terrain relief, to compare the differences between the inverted seismicity parameters and the observations, so as to further correct the inversion process or improve the reliability of the observations. In this regard, the geophysical and geological work of the exploration seismology and energy community can give a fairly good 3D velocity distribution [7]. For example, some can give more than a dozen logging curves for interpolating velocity models within square kilometers. Natural seismology is currently making good progress in obtaining more refined velocity models [22].

VS divides the surface of the rock mass into plains (including plateaus), mountainous areas, and loess plateaus; and even considers the slope of the stratification, which must not be as rough or simplified as the crustal velocity model when observing small or above earthquakes. Therefore, the correction and

inversion of the combined traditional relocation and velocity models commonly used in seismology [2] can be used (dynamically) if there are conditions for traditional relocation to ensure that the velocity model is as close to reality as possible. The current direct observation and inversion of the velocity model can provide basic monitoring guarantees, and the sensitivity of the velocity value error is equivalent to our general horizontal error (within ~ 20 meters [7]).

4. Data Processing and Interpretation Based on Microseismic Equivalent Focal Mechanism

4.1 Using the Shear Dislocation Focal Mechanism to Guide DMS

In Eq. (1), $x_{ij} = s_{ij} + n_{ij}$, but it is impossible to strictly separate the useful microseismic signal s_{ij} from the useless background noise n_{ij} . However, if the initial motion pattern of s_{ij} in each station is regular or similar (Fig. 1, Eq. (3)), and the time difference among stations receiving an initial tremor is calculated according to the known velocity model, then misaligning the station records in time (it is equivalent to moving each station to a reference point (migration)), we can stack the vector x_{ij} with s_{ij} and n_{ij} for a certain waveform in a time period.

Since the recordings are basically random or near-random, the stacking suppresses the random noise n_{ij} and enhances the useful s_{ij} . Therefore, we use the stacking of each time period to scan all the spatial points in the monitoring area, that is, the set of P , then squared, to obtain each E_P , which is the dimensionless microseismic released energy, which also reflects the correlation among stations and the space-time distribution of the minimum S/N.

Note that the above stack only applies to explosion or collapse event with single P-wave initial movement. Obviously, for general microseismic with shear characteristics, the polarity of any waveform cannot be directly confirmed by the case of $S/N < 1$. However, complex polarity distribution must be considered (Fig. 3 and Eq. (3)).

VS uses the shear dislocation focal mechanism to guide the DMS. Here, “guide” has two meanings: one is the accurate waveform vector to be extracted as mentioned in the previous section; the second is when data stacking for a certain period of time, the initial movement (regardless of the + or - polarity) of microseisms contained in the records of any one station is used as a reference, and all possible combinations of E_P from all other stations are obtained after the large scale calculation. And then the different combinations of E_P are observed, and that the E_P containing strong microseismic released energy in the sense of high probability is selected (i.e., the correlation coefficient of stations, also the minimum S/N). In the process, SH and SV waves are mainly used, of which their amplitudes are much larger than P’s. For spatial points without microseisms, the correlation of random background records in the seismic network is generally low.

4.2 Explanation of SRV Patterns

One of the important characteristics of microseisms is the shear dislocation focal mechanism. Chapter 2 also shows that the microseismicity of the final VS output may be described in Anderson’s discussion, i.e., the X-(diamond-shaped) shape and corresponding details in its shear zones (Figs. 2 and 4). The $E_P(t)$ obtained over different time periods is only a fraction of the total spatial activity over a longer period of time, and it is often not possible to see the relationship between the stress-strain field and the rupture fault immediately during microseismic monitoring (e.g., fracturing) as in a single large earthquake. But as we continue to add up these $E_P(t)$, we may see regular patterns.

We observed, counted, and analyzed the morphology of SRV (Stimulated Rock Volume) on 497 stages/layers (coalbed methane, conventional oil and gas, shale gas, etc.) that applied VS for more than a year from 2023 to 2025, as well as some qualified fracturing monitoring in the past [3]. The vast majority of microseismic monitoring ruptures are in layered oil and

gas reservoir structures, and SRV is just the main range of final microseismicity, or microseismic high-energy release zone, or the high probability of cracks effectively connecting fracture networks.

The seismic location of VS is similar to the traditional that: the large S/N after aligning the wave vector DMS of all stations at one point in space indicates that the microseismic energy here is more likely to be released. VS ground monitoring accuracy can reach 10 to 20 meters in the horizontal direction. Similar to the horizontal direction in the longitudinal shallow area, such as within kilometers, but the error may be several times higher than that in the horizontal direction for deep targets above kilometers [7]. Large vertical error is the cost of ground monitoring.

It seems difficult to give an appropriate SRV vertical height. However, most of the microseisms detected are

induced microseisms in stratified structures, such as fracturing monitoring, which are the result stacked by $E_p(t)$ at different time periods, as shown in Fig. 5, and based on the monitoring and estimation of BPM monitoring and mechanical analysis of the layered structure, it can be confirmed with confidence that the vertical height of the SRV is confined to the thin reservoir [3]. The horizontal distribution shows the subtle characteristics of the shear dislocation zone (Fig. 2) and/or the shear mechanism of the X-type (or part of it) described by Anderson (Fig. 5ad).

4.3 Equivalent Microseismic Focal Mechanism

According to the microseisms and their monitoring characteristics, including the concept of probability and mathematical statistics, VS uses the shear dislocation focal mechanism to guide the DMS. The primary

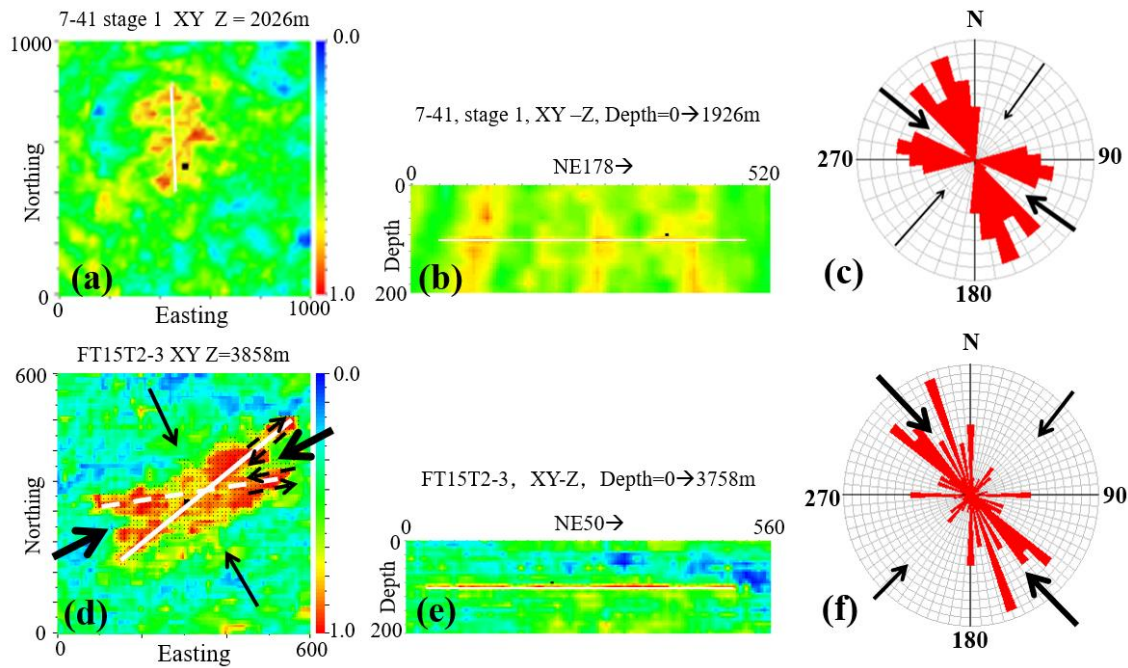


Fig. 5 (a) and (b): SRV distribution of fracturing stage with high probability of high rupture energy expression in 2D for well 7-41. (a): Plane 2D, geese flight. The solid white line is the main direction of SRV. The black dot is projection of the perforation segment of the inclined well. (b): The profile of the solid white line in a 2D plane, the white line is the tendency. The vertical error of the upper and lower parts of the reservoir is large. (d) and (e): same as (a) and (b); However, the scale is 600 m x 600 m in (d), and the conjugated fracture zone is represented by a virtual white line, and the vertical error above and below the reservoir is concentrated near the reservoir after a large number of accumulation of different time periods [3]. The dotted black arrow pairs indicate the dislocation direction of the crack zones. (c) and (f): the statistical rose plot of the main strike of the fault zone with high rupture energy distribution in each fracturing stage of the large shale gas horizontal well and the coal mine roof before mining, respectively; the latter is still able to identify X-shaped crack bands due to the presence of numerous laneways. In (c), (d), and (f), the thick and thin black arrow pairs represent the possible orientations of σ_1 and σ_3 respectively.

purpose is to make full use of the main rupture attribute of microseismic shear dislocation in a certain period of time, even if $S/N \leq 1$, to correctly extract the wave vectors, especially the S-wave vector with a large amplitude. On the other hand, when stacking and the initial motion symbol of the microseismics is not known, all possible initial motion combinations are tried on a large scale, and the $E_P(t)$ with a high probability of releasing energy from the microseismic is selected.

Each $E_P(t)$ of the VS monitoring output is only part of the final rupture net. The final space microseismicity after a large number of $E_P(t)$ superposition should also show the shear rupture mechanism, stress-strain relationship, and general observational characteristics of tectonic geology under the action of tectonic stress fields on a macroscopic or large scale. This is also an important condition for us to test the output of microseismic monitoring, or the characteristics converted base on the microseismicity. We define these as the equivalent microseismic focal mechanism of VS, which is the basis for the data processing and interpretation of far-field microseismic monitoring [1-3].

5. Necessary Conditions to Ensure Reliable Monitoring with High Probability

The R&D process of VS shows that microseismics and their monitoring characteristics determine that the conditions required for such monitoring are fine and harsh. It is difficult to give sufficient conditions to ensure the reliability of microseismic monitoring. However, based on the characteristics of microseismic monitoring, forward and inverted simulations, and a large number of experiments, many necessary conditions can be proposed to ensure reliable monitoring with high probability [1-4, 7].

The indispensable conditions for the reliability of far-field microseismic monitoring in identification and inspection in VS applications include:

(1) We should use seismic detectors with a lower natural frequency suitable for monitoring microseismics,

such as $\sim 5\text{Hz}$. It has a spiral shell that screws into the ground to maintain a high coupling to the earth.

(2) Each monitoring station of the seismic network should be at a quantitatively determined quiet location, and the discrete horizontal distribution covers the monitoring area in at least 2D.

(3) DMS must take into account shear rupture characteristics. Generally, P wave with much smaller amplitudes is rarely used (e.g. only at shallower areas), and S waves, namely SV and SH, that can carry much more energy to reach farther places, are generally used.

(4) We should use a statistically significant minimum number of stations, $N_{\min} (\geq 10 \pm 2)$. The seismic network should contain $\geq 2 \times N_{\min}$ of microseismic stations.

(5) Effective denoising, especially for teleseisms and ground machines, must be performed to make background noise recordings random or near-random.

(6) The lower limit of S/N (or the energy released, or the correlation between stations) output by DMS is $\geq \sim 1\%$, which is the threshold for the possible existence of microseismic (statistical results).

(7) Characteristic parameters with a quantitative range are studied and used to remove some E_P with remnant noise-coherent interference, and obtain those $E_P(t)$ or SRV(t) in time released by microseismicity.

(8) By accumulating all SRV(t), the final spatial distribution of SRV in the target domain is defined and judged in terms of probability and statistical significance.

The above conditions are confirmed on the basis of seismology, including seismometry, and a large number of experiments and applications, some are statistical, some are strict but can be satisfied, and some are in accordance with the monitoring principle to try to satisfy the requirements of better S/N. These conditions can be further quantitatively refined to specific values. Accordingly, a quality inspection system for data collection, observation network, data processing and interpretation has been established. These, coupled with the improvement of BPM, mine safety warning,

and small-micro seismic precursor before destructive earthquakes, etc. constitute microseismology, including microseismometry.

6. Conclusions

The main purpose of this paper is to emphasize the essence or first principle of microseismic monitoring: Any monitoring must first clarify the objective and its monitoring characteristics. The two important characteristics of microseismic are: tiny, and rupture with mainly shear dislocation mechanism. The monitoring characteristics obtained by the features are: often $S/N < 1$ from a few hundred meters away, and the traditional location fails; one hypocenter radiates longitudinal and transverse waves into space, and the amplitude and polarity of the waves change with different directions. The described monitoring characteristics, as shown in the title of this paper, can be called as the essence or first principle of microseismic monitoring. These problems without considering the essence are evident in many ground, well, mine safety, inversion velocity models, and the monitoring of small-micro seismic precursors before destructive earthquakes.

We take the R&D of VS as an example to illustrate: first, the microseismic information implied in the noise by implementing DMS. Second, the seismic wave vectors are correctly extracted from the 3-C records by using the far-field displacement solution generated by the shear fault dynamic coupled source, especially the shear wave vectors SV and SH with large amplitude, slow attenuation and long propagation. And third, the focal mechanism of passive or natural earthquakes, the stress-strain constitutive relationship in elastic mechanics, and the Anderson discussion in structural geology or rock mechanics are used to guide the DMS and microseismicity interpretation, and form an equivalent microseismic focal mechanism.

Because VS is based on the shear dislocation focal mechanism of passive microseisms and statistical concepts, there are the following differences between

VS and previous DMS or other microseismic monitoring methods: The pre-DMS used scalar or vertical component record is developed into the vector of each waveform radiated from the hypocenters; S waves are mainly used in VS, which have larger amplitude, slow attenuation, and long propagation. Guided by the shear dislocation mechanism, all possible arrival polarity combinations are calculated by VS for the low S/N records of all seismic stations, and the E_p with spatio-temporal distribution containing strong microseismic energy is selected as the most likely solution in the sense of probability. The morphological characteristics of microseismicity are predicted and also observed in VS, which conform to the shear dislocation mechanism, or the stress-strain relationship in the tectonic geological environment of the earth's crust. In order to connect with the general seismic energy levels and compare the energy levels of microseismicity in various places, the determination of equivalent microseismic magnitude was developed [23] in VS. And in long-term applications, VS proposes the necessary conditions for identifying, checking, and applying the first principle of microseismic monitoring, which are indispensable for high probability of reliability.

These greatly expand the scope of microseismic monitoring and improve the quality of monitoring, are applicable to the case of $S/N > 1$, and may also establish a solid foundation for microseismology, including microseismometry.

7. Discussions on Some Other Requirements for R&D of Microseismology

The R&D history of VS shows that microseismic monitoring is more difficult than monitoring stealth aircrafts and navigators, in which there exists a fluid separation over there, such that there is always some way to test their monitoring. In the face of the tiny microseisms with general $S/N < 1$ records, and at first glance, the microseismic information is completely submerged in background noise. To extract

microseismic information from records, it is necessary to first confirm that the essence of microseismics is passive earthquakes, which has a shear dislocation focal mechanism similar to that of natural earthquakes, and may use mathematical statistical concepts to establish monitoring principles; that is so called the First Principle.

To apply and reliably implement this monitoring principle, a large number of experiments have to be carried out to verify each parameter in data acquisition, processing, and interpretation. Among the 8 necessary conditions to ensure VS reliability with a high probability, the Items 7 and 8 were also summarized after repeatedly comparing the field noise sources and VS monitoring outputs in the recent 3 years.

The quality of microseismic instruments is one of the important prerequisites for reliable monitoring. To meet the requirements for real-time and high-quality microseismic monitoring, the engineer in developing seismic instruments should have: Professional foundation of automation electronics; Powerful programming ability to control instruments with embedded software; Adapting to the technical requirements of microseismic monitoring, and accepting the cooperation and strict inspection of microseismologists.

The requirements for the scientists in developing software of data processing and interpreting are similar. Any software and hardware R&D personnel should participate in practical applications. It has to emphasize here that the developers with a background of natural seismology should learn the fineness of exploration seismology and deep well technology, while those with a background in exploration seismology need to supplement the knowledge of the fault focal mechanism.

Most of the VS processes, from the data acquisition, the communication between the application party, the data processing and interpretation service, and other parties through the internet and telecommunication network, the data collation, denoising, data stacking in processing, the further denoising in the interpretation,

the determination of SRV morphology in space-time, the equivalent microseismic magnitude, and many statistical analysis, to the strict quality inspection of the data and methods at each stage, have formed effective and reasonable dynamic parameter groups. These have been basically automated, for which the process can be called the VS expert system.

It is so called because every step or method is based on the analysis of mathematics, seismology, geology, microseismic and its monitoring characteristics, a large number of experimental comparisons, and reasonable logic.

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