INTRODUCTION

Energy is the support of national development. In recent years, while increasing the technological measures for the exploitation of conventional oil and gas resources, more and more attention has been paid to the unconventional oil and gas resources. Unconventional reservoirs are often characterized by ultra-low permeability and porosity. Therefore, hydraulic fracturing technology, and in particular, three-dimensional reconstruction, has been applied to unconventional hydrocarbon development to generate artificial fractures, resulting in increased effective permeability of the reservoir. During the process of fracturing fluid injection, fractures created by reactivated shears or natural fractures can generate microseismic events. Microseismic monitoring is an effective method to explain relative parameters of artificial fractures (fracture height, length, azimuth, and zonal coverage) and to analyze fracture propagation during fracturing to guide hydraulic fracturing operation. In the past few decades, microseismic data have been used to interpret the characteristics of artificial fractures. Zhang et al. selected the alpha-shape method of the Kaspar Fischer structure based on Delaunay triangulation to compile an algorithm for calculating reservoir fracturing volume by using microseismic monitoring data. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
the problem of estimating irregular boundaries was solved by using microseismic event points. Zhu et al. used the high-quality processed microseismic data to quantitatively evaluate the extent of hydraulic fracturing at the test site.

Algorithms suitable for different strata and engineering backgrounds to increase the accuracy of source inversion and fracture interpretation have also been proposed. Zhu et al. used microseismic data from surface observation and moment tensor inversion to obtain the source mechanism of microseismic events. According to the actual hydraulic fracturing working environment, Zhang et al. proposed the method of monitoring fractures based on a combination of underground and surface monitoring; in a study of the influence of positioning accuracy of microseismic monitoring, Wen et al. evaluated the causes of the deviation of microseismic monitoring and proposed corresponding measures for improvement. Furthermore, they proposed the idea of local search technology combined with a global optimization genetic algorithm, which included combining microseismic observations with artificial wave observations to improve the technical route of the research. Hence, the accuracy of the spatial autocorrelation was improved. Yin et al. analyzed the influence of the correction of velocity model, velocity anisotropy, stratum dip angle, and multistage fracturing on a fine velocity model and positioning accuracy by combining theoretical and numerical simulation methods.

As mentioned above, many scientists have focused on improving the theoretical algorithm of microseismic reconstruction. However, they do not consider the field parameters (proppant amount and fracturing fluid volume) in the explanation process for fractures based on microseismic monitoring results. Therefore, here, we introduce an innovative method to delineate fractures using fracturing construction parameters and fracturing properties synchronously obtained by microseismic interpretations from 36 fracturing wells in Qinghai Oilfield. In this study, we define the communication mode between hydraulic fractures and natural fractures and classify fractured wells on this basis. The correction coefficients (volume correction coefficients, length correction coefficients, and height correction coefficients) are theoretically deduced and practically calculated, thus providing us a basis for field construction.

2 | DATA

Our method was applied to data collected from Qie-6 block, Qinghai Oilfield, which provides a large number of microseismic events to test the proposed techniques. The database can be divided into two different parts. The first includes the fracture morphological parameters including height, width, azimuth, and length obtained by microseismic interpretation results, and the other includes engineering parameters such as proppant amount, volume, fracturing fluid types, and viscosities during the fracturing process. Proppant amount and fracturing fluid volume are relative parameters in this study.

Kunbei Oilfield is located in the Kunbei fault terrace belt in the south of southwestern Qaidam Basin, China. The Kunbei fault terrace belt is the main fault terrace belt controlled by the Kunlun Mountains uplifting and compressing into the basin. We focus on Qie-6 block, controlled by Qie-6 fault in the south. It is situated in the eastern part of Kunbei Oilfield. Figure 1 shows the location of the Qie-6 block. The Paleocene Eocene developed from east to west in the sedimentary rocks of Kunbei area, and the bedrock contacted the Lule River Formation above it as a regional unconformity. The Jurassic and Cretaceous strata do not develop in the Qaidam Basin and distribute intermittently along the Qilian Mountains and the foothills of the Aljin Mountains. Since Cenozoic, the main deposits are braided river delta, lacustrine, and fluvial deposits in the foreland of inland mountains.
See Appendix A for detailed geological information of sedimentary strata in Qie-6 block. The Qie-6 block belongs to a low permeability reservoir with sandy conglomerate and has some natural fractures. In the development process, fracturing was carried out for some wells with poor oil-bearing properties.

According to the geological origin of the fractures, the fractures in the low permeability reservoirs in the Kunbei Oilfield can be divided into two types: the structural fractures formed under the action of tectonic stress fields and the diagenetic fractures formed during the sedimentation or diagenesis of the reservoirs. The structural fracture extending straight and appearing in multiple groups is considered to be the main fracture type in the bedrock reservoir based on the core analysis and thin section analysis of Qie-6 block’s coring (Figures 2 and 3). The structural fracture can be further divided into high-angle shear fracture, oblique intersection fracture, and near-horizontal shear fracture in terms of core analysis of the dip angle of the fracture (Figure 2). The fracture filled with minerals often cuts through gravel, and some of the fractures are dissolved with large openings (Figure 3). The extremely high drilling rate in the study area indicates the main fracture in the reservoir is a medium- and high-angle shear fracture.

At present, the development of the Qie-6 block faces two major difficulties. The first is that the in situ stress field in the Qie-6 block is poorly understood, the monitoring means and data of artificial fracturing are limited, and the extension orientation, extension height, and length of artificial fracture are not clear, which makes it difficult to clearly understand the laws of water flooding and residual oil distribution. In addition, there are many low-yield and low-efficiency wells in the Kunbei Oilfield. Repeated fracturing is required to improve the development effect. Therefore, it is very important to accurately characterize the artificial fractures in the six-cut block for the prefracturing evaluation work to guide refracturing construction.

## 3 | CHARACTERIZATION OF FRACTURE COMBINATION MODES IN QIE-6

### 3.1 | Classification of fracture combination patterns

The development of natural fractures in a reservoir as one of the main factors that influence the propagation of hydraulic fractures is the objective condition for forming complex fracture morphology or three-dimensional fracture networks (3D fracture reconstruction) after fracturing is carried out. On the contrary, a pair of simple symmetric fractures that cannot enable low permeability reservoirs to be explored and developed effectively will be formed if the natural disconnection is poorly developed. In recent years, many experimental and numerical studies have been conducted to reveal the law of artificial fracture behaviors when they encounter natural discontinuities. Considering modeling of fracture propagation is static which cannot truly model real natural fractures, a newly developed numerical approach was presented by Gaetano et al.\textsuperscript{23} to model the propagation of fractures through rock in real time using microbrittle dynamic theory. Hou et al.\textsuperscript{24} used a series of large-scale true triaxial experiments combined with acoustic emission monitoring to characterize the fracture initiation and propagation in a selected deep shale formation and pointed out that the natural fracture development state (fracture angle, width, and filling), stress regime, pumping rate, and procedure as well as viscosity of fracturing fluid ultimately influence the geometric form of the fracture. Tan et al.\textsuperscript{25} performed true triaxial tests on large laminated shale cores from Longmaxi shale outcrops to study the behavior of

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**FIGURE 2** Core analysis result chart of Qie-6 wells. Core is taken from four wells in Qie-6. Natural fractures and bedding development in core formation can be found from the graph.
complex fracture networks in the vertical plane. Obviously, the difficulty and method of shape characterization and correction of fractures are diverse for different network complexities. Therefore, it is necessary to classify and characterize the combination morphology of artificial fractures and natural fractures in fractured wells to provide a basis for effective signal identification and subsequent correction coefficient derivation of microseismic monitoring.

The natural fractures in the Qie-6 block reservoirs are mainly developed in the matrix and are poorly developed in sandstone compared with granite and slate. The dip angle of fractures is mainly between 30° and 70°. The horizontal geostress difference in the Qie-6 block is relatively high (6-12 MPa), and the maximum geostress azimuth is about NNE20-NNE25°. The propagation behavior of artificial fractures encountering natural fractures has been studied by many scholars from the aspects of numerical simulation and experiments. Zhang et al (2019) and Hou et al (2018) conducted indoor true triaxial physical simulation experiments, and they found that when artificial fractures encounter high-angle natural fractures, artificial fractures tend to propagate directly through natural fractures, and while encountering low-angle natural fractures, they tend to turn. According to test results of relevant physical models, when the horizontal stress difference is higher than 8-10 MPa, artificial fractures cannot communicate with natural fractures with a low dip angle. Only when the local stress difference is lower than 8 MPa, artificial fractures can possibly communicate with natural fractures with a high dip angle to form a complex fracture network.

In this study, conditions of in situ stress state and natural fracture development analysis results in the Qie-6 block are combined with indoor physical simulation experiment results to show three possibilities for the combination types between natural fractures and artificial fractures, as shown in Figure 4. (“HF” and “NF” represent the hydraulic fractures and nature fractures, respectively.) In the first type, natural fractures are not developed; the main hydraulic fracture is a single transverse cut fracture that does not communicate with the natural fracture (Figure 4A). In the third type, a natural fracture is developed; hydraulic fractures communicate with natural fractures, and as a result, complex networks are formed (Figure 4C). Type 2 is a transitional state between type 1 and type 3 (Figure 4B). This article will provide a novel method to determine which type the fracture combination state belongs to after fracturing in field fracturing wells.

3.2 | Research on classification method of fracture communication mode

When classifying and analyzing the compound mode of natural fractures and hydraulic fractures, the quantitative data used in the field are ultimately selected as the interpretation results of fracture length according to microseismic monitoring and the amount of proppant added in the field. There are two steps in the classification process. The first step is to judge the reliability of fracture parameters interpreted by microseismic monitoring and the amount of proppant added in the field. There are two steps in the classification process. The first step is to judge the reliability of fracture parameters interpreted by microseismic monitoring and the amount of proppant added in the field. There are two steps in the classification process. The first step is to judge the reliability of fracture parameters interpreted by microseismic monitoring and the amount of proppant added in the field. There are two steps in the classification process. The first step is to judge the reliability of fracture parameters interpreted by microseismic monitoring.

The second step is to establish indicators to classify combination modes. The reliability judgment of the microseismic data in the first step determines the choice of the evaluation method in the second step, so there are two cases in step 2:

1. When the results of microseismic monitoring and the amount of proppant added contradict, that is, the hydraulic fractures by microseismic monitoring are long, but the amount of proppant added in the field is small, the feasibility of microseismic interpretation results is...
low, and the classification is mainly based on the actual amount of proppant added in the construction.

2. The results of microseismic monitoring coincide well with the amount of sand added, that is, the amount of sand added is large and the hydraulic fracture interpreted by microseismic monitoring is long, and vice versa. Because of their strong correlation, principal component analysis can be used to define the two as a new principal component to reduce the dimensions of multiple variables and simplify the classification process.

The specific classification workflow is shown in Figure 5.

To quickly classify the numerous wells in the field, software for classifying fractured wells was developed on the visual basic 6.0 platform based on the above classification method. The software supports user-defined classification standards. The output results mainly include features such as the type of fracturing wells and classification standards. Its operation interface is shown in Figure 6.

3.3 Classification process of fracturing wells in Qie-6

Taking the Qie-6 block as an example, data were collected and collated for fracture parameters, and proppant amount was interpreted by microseismic monitoring of 36 fracturing wells in the block. The classification process of fracturing wells will be described in detail in this study.

After data processing, the observation matrix of two-dimensional random variables composed of proppant amount, fracture length, and the mean vector is obtained as follows:

\[
\bar{X} = \begin{bmatrix} 15.05 \\ 170.98 \end{bmatrix}
\]
According to the knowledge of mathematical statistics, the A matrix of two-dimensional random variables in the Qie-6 block is calculated as follows:

\[
A = \begin{bmatrix}
816.56 & 4657.86 \\
4657.86 & 240389.84
\end{bmatrix}
\]

The unbiased estimation of samples is used instead of the total covariance.

\[
S^* = \begin{bmatrix}
22.07 & 125.89 \\
125.89 & 6497.02
\end{bmatrix}
\]

From the covariance matrix of the sample, the value of the sample is found to be quite different. To avoid the large number making the decimal part negligible, the correlation coefficient matrix can be used to solve the principal component of the Qie-6 block. According to the above-mentioned sample covariance matrix, the correlation coefficient matrix of the two-dimensional random variables in the process of the Qie-6 block classification can be calculated as follows.

\[
\rho = \begin{bmatrix}
1 & 0.33 \\
0.33 & 1
\end{bmatrix}
\]

The eigenvectors of the correlation coefficient matrix of the Qie-6 block are obtained as per the correlation coefficient matrix. The calculated value of the first principal component contribution rate is 0.79, which can meet the fracturing construction requirements.

\[
\lambda_1 = 1.58
\]

\[
\lambda_2 = 0.42
\]

Then, the eigenvector corresponding to the first principal component is given as follows.

\[
X = \begin{bmatrix}
0.5 \\
0.87
\end{bmatrix}
\]

Therefore, the first principal component can be expressed as

\[
F_1 = 0.5x_1 + 0.87x_2
\]

1. Classification standard delineation

There are many fracturing wells in the Qie-6 block. To further refine the fracturing wells, the second and third types can be subdivided into two subtypes according to the complexity of hydraulic fractures communicating with natural fractures, and then, the critical values of each type can be determined.

a. Classification standard based on principal component analysis

Obviously, the higher the principal component score is, the greater the amount of sand added to construction and the longer hydraulic fractures are, indicating a more complex fracture compound mode. Combined with field analysis, the classification standard of the communication mode based on the score of the principal component is given. The classification standard is shown in Table 1.

2. Classification standard based on proppant amount

According to the requirement of field construction, when the ratio of the length of fractures to proppant amount is less than 10, it is considered that the actual construction proppant amount does not correspond well with the fracture length from the microseismic interpretation. The length of microseismic interpretation fractures is considered to not contribute to the classification results and cannot be used as a classification standard. In this case, the classification standard based on proppant amount is shown in Table 2.

3. Classification results

By inputting the parameters of 36 wells to be determined one by one into the software, the classification results of 36 wells to be determined in the Qie-6 block can be obtained, as shown in Table 3.

Statistical analysis of well types is shown in Figure 7. It can be seen from the bar graph that the number of type 3 fractures in the Qie-6 block is the largest and that of type 1 is the least.

4. Deduction of correction coefficient for microseismic interpretation results in Qie-6

When the stress conditions on Earth are changed due to disturbances (like hydraulic fracturing), microseismicity occurs in the stress loading or pore pressure, resulting in sudden movement between rock elements. Therefore,

| Types | Subtypes | Principal component values |
|-------|----------|----------------------------|
| 1     | –        | <130                       |
| 2     | I        | 130-160                    |
|       | II       | 160-200                    |
| 3     | I        | 200-250                    |
|       | II       | >250                       |

TABLE 1 Classification standard table based on principal component values
numerous microseismic signal event points are produced during high displacement fracturing, which is an effective technology to explain the physical form of artificial fractures. Liu et al.\textsuperscript{29} pointed out that reactivation of natural fractures or faults, previous hydraulic fractures, stratigraphic boundaries, and operational noise can also generate microseismic events. The detection events can help monitor fracture orientation and location, but they cannot explain proper dimensions or the underlying hydraulic fracture structure.\textsuperscript{30} Therefore, it is unreasonable to interpret the effective fracture shape after fracturing by using microseismic monitoring data only, which results in very confusing fracture morphology interpretation results which are different from reality. Therefore, it is necessary to correct the microseismic interpretation results in combination with field construction parameters to gain greater insight into the fracture dimensions that will ultimately affect production. In this study, we propose a new fracture morphology correction method based on the following three assumptions, and the volume correction coefficient, height correction coefficient, and width correction coefficient of fractures are derived by direct application to fracture morphology evaluation after in situ fracturing.

1. The proppant particles are suspended in high viscous fracturing fluids, and the sand-carrying fluids propagate approximately in the form of plungers in the fractures.
2. The sand ratio has no effect on the filtrate loss characteristics of the sand-carrying fluid.
3. The fracture is a symmetrical double-wing vertical crack, and the horizontal section of the fracture is elliptical.

As shown in Figure 8, to simplify the calculation, we considered the fracture model to be calculated as a Perkins-Kern-Nordgren model.

4.1 Correction factor deduction

\( V_i \) is the effective amount of fracturing fluid. It has the following relations with the volume of prefluids \( V_{fp} \) and sand-carrying fluids \( V_{fs} \).\textsuperscript{31}

\[
V_i = V_{fp} + V_{fs}
\]  

(1)

In this study, the concept of total fractures-making efficiency \( E_f \) in the formula of continuous change of sand injection ratio proposed by KG Nolte is quoted, which represents the total fractures-making efficiency of the preceding fluid and the sand-carrying fluid.

\[
E_f = \frac{2V_{frac}}{V_i} = 1 - \sqrt{\frac{V_{fp}}{V_i}}
\]

(2)
According to the traditional hydraulic fracturing theory, a nearly symmetrical double-wing fracture will be formed around the wellbore during the fracturing process. The volume of one side fracture is defined as $V_{frac}$, and the volume of the whole artificial fracture is $2V_{frac}$.

According to the above PKN model, the maximum fracture height $W_{max}$ can be obtained from the following calculation.

$$W_{max} = 2a \left[ \frac{1}{60} \frac{(1 - \nu^2) Q \mu L}{E} \right]^{1/4}$$  \hspace{1cm} (3)

Here, $W_{max}$ denotes the maximum fracture height of Newtonian fluid in laminar flow; $a$ and $E$ denote elastic modulus and Poisson’s ratio of formation to be fractured, respectively. $L$ is half-fracture length. The viscosity of fracturing fluid is given by $\mu$, and displacement is $Q$. $a$ is the calculation coefficient in the formula of fracture parameter calculation. Wu explained the value of pressure distribution coefficient $B$.

Based on the basic Equations (1)-(3), the following formulas are deduced in this paper. The deduction process is as follows.

When deriving the correction coefficient, the effective fracture fluid $V_j$ can be derived using Equation (1) according to the amount of sand-carrying fluid and the amount of prefluid in the field. The total fracture efficiency $E_f$ can be obtained by Equation (2). Finally, the fracture volume can be calculated as shown in Equation (4).

$$V_{frac} = E_f V_j / 2$$  \hspace{1cm} (4)

In addition,  

$$V_{frac} = \pi W_{max} LH$$  \hspace{1cm} (5)

Equation (5) is combined with Equation (3).

$$V_{frac} = \pi 2a \left[ \frac{1}{60} \frac{(1 - \nu^2) Q \mu}{E} \right]^{1/4} L^{5/4} H$$  \hspace{1cm} (6)

**TABLE 4** Classification results of fractured wells in Qie-6

| Types | Subtypes | Volume correction factor |
|-------|----------|-------------------------|
| 1     | –        | 0.78                    |
| 2     | I        | 0.9                     |
| II    |          | 1.02                    |
| 3     | I        | 1.06                    |
| II    |          | 1.11                    |

$Q$ takes total ground displacement, $W_{max}$ is half of the total ground displacement, $a = 1.5$; here, $a = 1.26$ because of the total ground displacement.

Equation (6) is combined with Equation (4).

$$L^{5/4} H = \pi 4a \left[ \frac{1}{60} \frac{(1 - \nu^2) Q \mu}{E} \right]^{1/4}$$  \hspace{1cm} (7)

$L^{5/4} H$ calculated using Equation (7) is taken as the theoretical value $\left< L^{5/4} H \right>_{T}$, and the actual value $\left< L^{5/4} H \right>_{W}$ of the fracture result is interpreted by microseismic monitoring. The ratio of the two is recorded as the volume correction coefficient $B_{V}$, that is

$$B_{V} = \frac{\left[ L^{5/4} H \right]_{T}}{\left[ L^{5/4} H \right]_{W}}$$  \hspace{1cm} (8)

The volume correction coefficient $B_{V}$ is inverted to the result of microseismic interpretation to obtain the correction coefficients of fracture length and height. The derivation process is as follows:

$$B_{V} \left[ L^{5/4} H \right]_{W} = \left[ L^{5/4} H \right]_{T}$$  \hspace{1cm} (9)

Since the calculation of fracture volume is based on a simple PKN model, in this paper we considered that the fracture volume can be calculated by using the following formula:

$$V = HLW$$  \hspace{1cm} (10)

In Equation (10), $H$, $L$, and $W$ represent the height, length, and width of hydraulic fractures, respectively.

The corresponding volume correction coefficients can be calculated by Equation (11):

$$B_{V} = B_{H} B_{L} B_{W}$$  \hspace{1cm} (11)

Here, $B_{H}$, $B_{L}$, and $B_{W}$ represent the correction coefficients of fracture height, length, and width, respectively.
In this paper, it is assumed that the width of fractures in microseismic interpretation is compound with actual conditions, and the width correction coefficient is 1, which can be omitted. Hence, \[ B_v = B_H B_L \] (12)

Equation (12) is brought into Equation (9) to obtain (13) and (14).

\[ B_H B_L \left[ L_w^{5/4} H \right] = \left[ L_T^{5/4} H_T \right] \] (13)

\[ B_H H_a B_L L_w^{5/4} = L_T^{5/4} H_T \] (14)

In order to facilitate the derivation, some skillful transformations are made here, and the intermediate variable “a” is introduced.

\[ a H_w L_w^{5/4} = L_T^{5/4} H_T \] (15)

Comparing Equations (14) and (15), we can find that:

| Types | Subtypes | \( B_v \) | \( a \) | \( B_L \) | \( B_H \) |
|-------|----------|----------|----------|----------|----------|
| 1     | –        | 0.78     | 0.897444 | 0.873492 | 0.897444 |
| 2     | I        | 0.9      | 0.95507  | 0.944156 | 0.95507  |
|       | II       | 1.02     | 1.009695 | 1.012133 | 1.009695 |
| 3     | I        | 1.06     | 1.024743 | 1.031023 | 1.024743 |
|       | II       | 1.11     | 1.048411 | 1.060876 | 1.048411 |

**TABLE 5** Statistical tables for correction coefficients of fractured wells in Qie-6

**TABLE 6** Correction result table of fracture morphology in typical wells

**FIGURE 10** A. Microseismic fracture regression diagram of well 10-12. B. Microseismic fracture correction result of well 10-12. The comparison of precorrection and postcorrection of fracture surface type 1 fracture communication mode (taking 10-12 as typical well). The scatter points in the graph represent the microseismic monitoring data in the field, and the surface represents the fracture surface fitted by the random consistency algorithm.

In this paper, it is assumed that the width of fractures in microseismic interpretation is compound with actual conditions, and the width correction coefficient is 1, which can be omitted. Hence, \[ B_v = B_H B_L \] (12)

Equation (12) is brought into Equation (9) to obtain (13) and (14).

\[ B_H B_L \left[ L_w^{5/4} H \right] = \left[ L_T^{5/4} H_T \right] \] (13)

\[ B_H H_a B_L L_w^{5/4} = L_T^{5/4} H_T \] (14)

In order to facilitate the derivation, some skillful transformations are made here, and the intermediate variable “a” is introduced.

\[ a H_w L_w^{5/4} = L_T^{5/4} H_T \] (15)

Comparing Equations (14) and (15), we can find that:
The volume correction coefficient can be deduced according to Equation (12).
\[
a^{5/4} = B_L \tag{16}
\]
\[
a = B_H \tag{17}
\]
\[
a^{9/4} = B_V \tag{18}
\]
The intermediate variable $a$ can be inversely solved by Equation (18). From Equations (16) and (17), $B_L$ and $B_H$ can be obtained.

### 4.2 Correction coefficient acquisition and analysis

1. Correction factor of volume

According to the classification results of the fractured wells in the Qie-6 block, the volume correction data $B_V$ of type 1, type 2, and type 3 as well as their subclasses can be obtained. The volume correction coefficients of each type were taken as the average values of the volume correction coefficients of all the single wells in this type. Here, the elastic modulus of the six blocks is 336 GPa, and Poisson’s ratio is 0.2. The average value of fracture length of two wings calculated by microseismic monitoring results was considered as the half-length of fracture.

By mining the information in Table 4, we obtained the following conclusions:

- a. The volume correction coefficient of type 1 is less than 1, which indicates that the length and height of fractures interpreted by microseismic monitoring are larger than those in reality. Because the shape of this type of fractures is simple and the rate of drilling natural fractures is low, it is difficult to form complex fracture communication modes. The results of microseismic interpretations of the volume should be corrected in the negative direction.

- b. The overall volume correction coefficient of type 2 is close to 1, that is, the length and height of artificial
fractures interpreted by microseismic are almost consistent with the actual construction, and the volume correction coefficient of subtype I is smaller than that of subtype II because the fracture morphology of the latter is more complicated than that of the former.

c. The volume correction coefficient of type 3 is greater than 1, which denotes that the length and height of fractures interpreted by microseismic monitoring are smaller than those by actual operation. The complex combination of artificial fractures with hydraulic fractures in type 3 fracturing wells can explain this phenomenon. In this case, the secondary fractures around the main fractures should be considered when microseismic interpretation is performed. Furthermore, the correction coefficient of subclass I is lower than that of subclass II, as is the case with type 1. The rule that the more complex the combination model is, the larger the correction coefficients are is verified again.

d. With the increase in the complexity of fractured fractures, the correction coefficient shows an upward trend, as shown in Figure 9.

2. Correction factors of fracture length and height

Based on the calculation results of the volume correction factor of the Qie-6 block, the correction coefficients $B_L$ and $B_H$ of the three types and their subclasses are calculated according to Equations (9)-(11). The statistical results are shown in Table 5.

3. Comparative analysis of microseismic correction results

FIGURE 14 Comparison of fracture length before and after correction. A, is comparison bar chart of correction results of fracture length in type 1 fracture combination mode. B and C, are bar diagrams for comparing the corrected results of fracture length in fracture combination mode of two subclasses of type 2. D and E, are bar diagrams for comparing the corrected results of fracture length in fracture combination mode of two subclasses of type 3.
Liu et al. developed a robust three-dimensional seam mesh reconstruction method RFM based on random simulation consistency (RANSAC) and established a geometric model of single fractures with random polygons by comparing the results of laboratory true triaxial hydraulic fracturing experiments. Taking well 10-12, well 5-17, and well 4-13 in Qie-6 block as three typical wells, the three-dimensional artificial fracture surface was reconstructed based on RANSAC according to the site microseismic event points. The correction coefficients of fracture parameters (fracture height and fracture length) of each well calculated above were used to correct the reconstructed fracture surface network (Table 6). The results are shown in Figures 10-12. The figure shows the difference in fracture surface before and after correction occurs in type 1 wells and type 3 wells (Figures 10 and 12), while the results of type 2 wells are close to those of microseismic interpretation (Figure 11).

The results before and after the correction of fracture parameters (height and length) are counted, and a contrast bar chart is drawn (Figure 13 is the comparison of fracture height

| Types | Subtypes | Well name | Average fracture height/m | Average half-fracture length/m | Average fracture height (corrected)/m | Average half-fracture length (corrected)/m |
|-------|-----------|-----------|--------------------------|-------------------------------|--------------------------------------|------------------------------------------|
| 1     | –         | W4-17     | 9.8                      | 20.55                         | 8.794951                             | 17.95026                                 |
|       |           | W7-5      | 5.4                      | 67.35                         | 4.846198                             | 58.82969                                 |
|       |           | W10-12    | 16.1                     | 64.28                         | 14.44885                             | 56.14807                                 |
|       |           | W8-10     | 9.4                      | 67.15                         | 8.435974                             | 58.65499                                 |
|       |           | W5-28     | 13                       | 66.79                         | 11.66677                             | 58.34053                                 |
| 2     | I         | W5-17     | 15.6                     | 95.55                         | 15.75124                             | 96.70931                                 |
|       |           | W4-12     | 19                       | 90.5                          | 19.18421                             | 91.59804                                 |
|       |           | W4-15     | 10.2                     | 72.1                          | 10.29889                             | 72.97479                                 |
|       |           | W7-7      | 11.9                     | 76.5                          | 12.01537                             | 77.42817                                 |
|       |           | W5-13     | 12.5                     | 95.1                          | 12.62119                             | 96.25385                                 |
|       |           | W11-10    | 19.7                     | 89                            | 19.89099                             | 90.07984                                 |
|       |           | W6-14     | 15.6                     | 95.55                         | 15.75124                             | 96.70931                                 |
|       | II        | W7-3      | 14.1                     | 72.86                         | 13.46649                             | 68.79121                                 |
|       |           | W8-13     | 12.2                     | 68.05                         | 11.65185                             | 64.24982                                 |
|       |           | W9-9      | 15.8                     | 73.205                        | 15.09011                             | 69.11694                                 |
|       |           | W9-11     | 22.7                     | 79.95                         | 21.68009                             | 75.48527                                 |
|       |           | W10-6     | 17.5                     | 71.45                         | 16.71373                             | 67.45995                                 |
|       |           | W6-22     | 9                       | 77.7                          | 8.59563                              | 73.36092                                 |
| 3     | I         | W4-16     | 18.1                     | 118.35                        | 18.54785                             | 122.0216                                 |
|       |           | W4-14     | 9.6                      | 131.6                         | 9.837533                             | 135.6826                                 |
|       |           | W9-7      | 21.4                     | 110.6                         | 21.9295                             | 114.0311                                 |
|       |           | W6-11     | 16.6                     | 85.2                          | 17.01073                             | 87.84316                                 |
|       |           | W8-15     | 13.35                    | 65.775                        | 13.68032                             | 67.81554                                 |
|       |           | W6-10     | 15.2                     | 70.8                          | 15.57609                             | 72.99643                                 |
|       |           | W8-6      | 9.2                      | 68.95                         | 9.427636                             | 71.08904                                 |
|       |           | W6-6      | 9.6                      | 78.35                         | 9.837533                             | 80.78065                                 |
|       |           | W3-13     | 11.9                     | 64.925                        | 12.19444                             | 66.93917                                 |
|       |           | W7-3      | 14.1                     | 72.86                         | 14.44888                             | 75.12034                                 |
|       |           | W7-5      | 5.4                      | 67.35                         | 5.53612                              | 69.4394                                 |
|       | II        | W6-18     | 8.35                     | 90.075                        | 8.754232                             | 95.55841                                 |
|       |           | W3-15     | 8.9                      | 95.475                        | 9.330858                             | 101.2871                                 |
|       |           | W4-13     | 10                       | 92.3                          | 10.48411                             | 97.91885                                 |
|       |           | W5-7      | 12.95                    | 71.15                         | 13.57692                             | 75.48133                                 |
|       |           | W10-13    | 14.05                    | 77.125                        | 14.73017                             | 81.82006                                 |
Based on the interpretation results of the microseismic monitoring data of artificial fracturing and considering the length and height of the corrected artificial fractures (Table 7), dip angle, and strike, the fractured slice model was generated using Petrel software (Figure 15), which provides more accurate geological background for the refracturing in Qie-6 as well as for the selection of production water injection wells and layers.

### CONCLUSIONS

1. According to the classification criteria defined in this paper, the number of type 3 wells is the largest and the number of the type 1 wells is the least. Thus, the communication between hydraulic fractures and natural fractures in Qie-6 is more complicated, and the effect of manual transformation is more obvious.

2. Volume correction coefficient, fracture length correction coefficient, and fracture height correction coefficient increase with the complexity of the communication between artificial and natural fractures.

3. For the Qie-6 block, the correction coefficients of the type 1 communication model and the second-class I subclass are less than 1, that is, the interpretation results of microseismic monitoring are too large regardless of the reconstruction volume, fracture length, and fracture height and should be corrected in the negative direction; on the contrary, the correction coefficients of type 3 and the second-class II subclass are greater than 1. Thus, correction should be performed in the positive direction.

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### CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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APPENDIX A

A SEDIMENTARY STRATIGRAPHIC GEOLOGICAL INFORMATION OF QIE-6 BLOCK

| Formation   | Lithology                                      | Sedimentary facies and conformity                                      |
|-------------|------------------------------------------------|-----------------------------------------------------------------------|
| Lulehe      | Purple-red mud, sand, and gravel mixed         | The Piedmont delta deposit is the oldest Cenozoic sedimentary stratum. Its wide distribution lithology varies greatly in Kunbei area. The exposed thickness is 86-830 m, and the underlying strata are in angular unconformity contact |
| Lower Ganchaigou | Light gray conglomerate, sandstone, and argillaceous | Lower Ganchaigou Formation is widely exposed in Kunbei area and has integrated or pseudointegrated contact with the underlying Lule River Formation. The typical lake facies sedimentary thickness is about 680 M |
| Upper Ganchaigou | Gray sandstone or gray calcareous mudstone interbedded with sandy mudstone | The strata of this formation are generally in conformity with the Lower Ganchaigou Formation underlying the whole basin |
| Youshashan  | Green-gray conglomerate sandstone, interbedded with brown-gray sandstone and brown sandy mudstone | Its upper and lower strata are continuous sedimentation and integrated contact |
| Shizigou    | Yellow-gray sandstone, calcareous mudstone, and brown sandy mudstone | The strata of this formation are distributed in most anticlinal structures in the basin |
| Qi ge quan  | Thick-layered conglomerate and shallow gray sandy mudstone interbedded, often accompanied by salt, gypsum, marl, and other sediments | The thickness of the formation varies greatly, and there is an angular unconformity contact with underlying strata in the southwestern margin of the basin |

APPENDIX B

PRINCIPAL COMPONENT ANALYSIS AND ITS APPLICATION IN QIE-6 BLOCK

In this paper, the correlation between proppant amount and fracture length is considered, and the principal component analysis theory is used to merge the two variables into one variable to simplify the analysis process. Following is a general procedure of principal component analysis and its practical application in this paper.

GENERAL DESCRIPTION

PRINCIPAL COMPONENT ANALYSIS THEORY

Assuming that there are \( p \) indices in the practical problem we are discussing, we regard these \( p \) indices as \( P \) random variables and record them as \( X_1, X_2, \ldots, X_p \). Principal component analysis (PCA) is to transform the problem of \( P \) indices into the problem of linear combination of \( P \) indices, and these new indices \( F_1, F_2, \ldots, F_k \) \((k < p)\), according to the principle of retaining the main amount of information, fully reflects the information of the original indicators and is independent of each other.

\[
F_1 = \mu_1 X_1 + \mu_2 X_2 + \ldots + \mu_p X_p \\
F_2 = \mu_1 X_1 + \mu_2 X_2 + \ldots + \mu_p X_p \\
\vdots \\
F_k = \mu_1 X_1 + \mu_2 X_2 + \ldots + \mu_p X_p 
\]

PRINCIPAL COMPONENT ANALYSIS STEPS

CALCULATING SAMPLE MEAN VECTOR \( \bar{X} \) AND COVARIANCE \( S \)

Let \( X \) be a \( p \)-dimensional random variable, with \( N \) samples, and each sample observes \( P \) indices, arranges the original data, and obtains the observation matrix of \( X \).

\[
X = \begin{bmatrix}
X_{11} & X_{12} & \ldots & X_{1P} \\
X_{21} & X_{22} & \ldots & X_{2P} \\
\vdots & \vdots & \ddots & \vdots \\
X_{n1} & X_{n2} & \ldots & X_{nP}
\end{bmatrix} = (X_1, X_2, \ldots, X_p)
\]

Here,

\[
X_i = \begin{bmatrix}
X_{i1} \\
X_{i2} \\
\vdots \\
X_{ni}
\end{bmatrix}
\]
Calculating sample mean vector $\bar{X}$ and covariance $S$ based on mathematical statistic knowledge.

$$\bar{X} = \left( \bar{X}_1, \bar{X}_2, \ldots, \bar{X}_p \right)$$

$$S = \begin{bmatrix}
  s_{11} & s_{12} & \cdots & s_{1p} \\
  s_{21} & s_{22} & \cdots & s_{2p} \\
  \vdots & \vdots & \ddots & \vdots \\
  s_{p1} & s_{p2} & \cdots & s_{pp}
\end{bmatrix} = \begin{bmatrix}
  \text{var}(X_1) & \text{cov}(X_1, X_2) & \cdots & \text{cov}(X_1, X_p) \\
  \text{cov}(X_2, X_1) & \text{var}(X_2) & \cdots & \text{cov}(X_2, X_p) \\
  \vdots & \vdots & \ddots & \vdots \\
  \text{cov}(X_p, X_1) & \text{cov}(X_p, X_2) & \cdots & \text{var}(X_p)
\end{bmatrix}$$

$$\bar{X}_p = \frac{1}{n} \sum_{i=1}^{n} x_{ip}$$

**SOLVE THE CHARACTERISTIC EQUATION**

$[S - \lambda I] = 0$, WHERE $I$ IS THE UNIT MATRIX

Let the covariance matrix of $X$ be expressed as follows:

$$S = \begin{bmatrix}
  \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1p} \\
  \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2p} \\
  \vdots & \vdots & \ddots & \vdots \\
  \sigma_{p1} & \sigma_{p2} & \cdots & \sigma_{pp}
\end{bmatrix}$$

Since $S$ is a nonnegative definite symmetric matrix, it can be obtained by using the knowledge of linear algebra. There must be an orthogonal matrix $U$, so that

$$U'^{T}SU = \begin{bmatrix}
  \lambda_1 & \cdots & 0 \\
  \vdots & \ddots & \vdots \\
  0 & \cdots & \lambda_p
\end{bmatrix}$$

where $\lambda_1, \lambda_2, \ldots, \lambda_p$ are the characteristic roots of $S$, and it may be assumed that $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_p$. $U$ is an orthogonal matrix consisting of eigenvectors corresponding to eigenvalues.

$$U = \left( U_1, U_2, \ldots, U_p \right) = \begin{bmatrix}
  u_{11} & u_{12} & \cdots & u_{1p} \\
  u_{21} & u_{22} & \cdots & u_{2p} \\
  \vdots & \vdots & \ddots & \vdots \\
  u_{p1} & u_{p2} & \cdots & u_{pp}
\end{bmatrix}$$

Here,

$$U_i = \begin{bmatrix}
  u_{i1} \\
  u_{i2} \\
  \vdots \\
  u_{in}
\end{bmatrix}$$

Then, the first principal component expression is as follows:

$$F_1 = \mu_{11}X_1 + \mu_{21}X_2 + \cdots + \mu_{p1}X_p$$

If the information of the first principal component is not enough, we need to find the second principal component. Similarly, under constraint $\text{cov}(F_1, F_2)$, find the second principal component:

$$F_2 = \mu_{12}X_1 + \mu_{22}X_2 + \cdots + \mu_{p2}X_p$$

Considerations:

According to mathematical statistics, sample covariance matrix $S$ is not unbiased estimation of variance of random variables, so unbiased estimation $S^{*}$ will be used to estimate variance of random variables. There is the following relationship between them.

$$S^{*} = \frac{n}{n-1} S$$

It is worth noting that $X_1, X_2, \ldots, X_p$ are not uniform in dimension and the difference in numerical values is too large; therefore, the correlation coefficient matrix $\rho$ is often used in the process of principal component analysis.

$$\rho = \begin{bmatrix}
  \rho_{11} & \rho_{12} & \cdots & \rho_{1p} \\
  \rho_{21} & \rho_{22} & \cdots & \rho_{2p} \\
  \vdots & \vdots & \ddots & \vdots \\
  \rho_{p1} & \rho_{p2} & \cdots & \rho_{pp}
\end{bmatrix}$$

Here,

$$\rho_{ij} = \frac{s_{ij}}{\sqrt{s_{ii}s_{jj}}}$$

Therefore, when the values of the elements in the observation matrix $X$ are quite different, the calculation of principal components by using the correlation coefficient matrix $\rho$ can be considered.

**APPLICATION OF PRINCIPAL COMPONENT ANALYSIS THEORY IN QIE-6**

In this paper, setting $X$ as a two-dimensional random variable, which consists of sand addition and fracture length, its observation matrix is obtained from the corresponding proppant amount and fracture length of 36 wells in Qinghai Oilfield (data can be referred to Appendix C). It can be expressed as follows:
The first list of matrices represents the amount of sand added to 36 wells, such as $Q_1$ representing the amount of proppant added to the first well.

The second column represents the sum of the length of the double-wing hydraulic fractures in 36 wells, such as $L_1$ representing the double-wing fractures in the first well.

Referring to the procedure of solving principal component in B1.1 of Appendix B, the mean vector of $X$ and the matrix of correlation coefficient are obtained.

$$X = \begin{bmatrix} Q_1 & L_1 \\ Q_2 & L_2 \\ \vdots & \vdots \\ Q_{36} & L_{36} \end{bmatrix}$$

The unbiased estimation $S^*$ of samples is used instead of the total covariance (the method to calculate $S^*$ refers to the method of $S^*$ in B1.2.2 of Appendix B).

$$S^* = \begin{bmatrix} 22.07 & 125.89 \\ 125.89 & 6497.02 \end{bmatrix}$$

From the covariance matrix of samples, it can be found that the values are quite different. In order to prevent the phenomenon that large numbers eat decimal numbers, the principal components of Qie-6 blocks are solved based on the correlation coefficient matrix $\rho$. According to the above-mentioned sample covariance matrix, the classification correlation coefficient matrix $\rho$ of Qie-6 block is obtained (the method to calculate $\rho$ refers to the method of $\rho$ in B 1.2.2 of Appendix B).

$$\rho = \begin{bmatrix} 1 & 0.33 \\ 0.33 & 1 \end{bmatrix}$$

Then, the first principal component expression of the block is calculated.

The eigenvectors of the correlation coefficient matrix of the Qie-6 block are obtained as per the correlation coefficient matrix. The calculated value of the first principal component contribution rate is 0.79, which can meet the fracturing construction requirements.

$$\lambda_1 = 1.58$$

$$\lambda_2 = 0.42$$

Then, the eigenvector corresponding to the first principal component is given as follows.

$$u_1 = \begin{bmatrix} 0.5 \\ 0.87 \end{bmatrix}$$

Therefore, the first principal component can be expressed as

$$F_1 = 0.5x_1 + 0.87x_2$$
### APPENDIX C

**ORIGINAL FRACTURING DATA OF QIE-6 BLOCK**

| Well name | X         | Y         | Fracturing horizon | Fracturing intervals | Proppant amount m³ | Sand ratio | Hydraulic fractures |
|-----------|-----------|-----------|--------------------|----------------------|--------------------|------------|---------------------|
|           |           |           |                    |                      |                    |            |                     |
| W4-12     | 16 337 269.8 | 4 187 695.7 | II-9 II-10 II-11  | 2050.20-2059.80      | 5                  | 10.98      |                     |
| W4-15     | 16 337 177.8 | 4 187 176.7 | II-10 II-11        | 2060.00-2066.50      | 13.5               | 19.64      |                     |
| W5-7      | 16 333 827.8 | 4 188 022.7 | II-9               | 2067.40-2069.20      | 6                  | 17.32      |                     |
| W10-12    | 16 335 222.8 | 4 185 895.7 | II-7 II-8 II-8    | 2098.60-2107.80      | 11                 | 25.89      |                     |
| W8-10     | 16 334 964.8 | 4 188 848.7 | II-10 II-11       | 1978.2-1983.7        | 11                 | 26.47      |                     |
| W5-28     | 16 334 905.3 | 4 187 848.2 | II-10 II-10 II-11 | 2104.00-2106.00      | 13                 | 24.22      |                     |
| W7-3      | 16 333 025.8 | 4 188 372.7 | II-10 II-11       | 2119.40-2126.00      | 14                 | 22.98      |                     |
| W8-9      | 16 334 892.8 | 4 187 620.7 | II-10 II-11 II-11 | 2047.70-2056.50      | 16                 | 20.75      |                     |
| W9-11     | 16 335 091.8 | 4 186 374.7 | II-10 II-10 II-10 | 2080.20-2085.50      | 11                 | 21.57      |                     |
| W10-6     | 16 333 402  | 4 186 943  | II-7 II-8 II-9    | 2050.70-2060.60      | 13.5               | 19.64      |                     |
| W6-22     | 16 336 015  | 4 186 814.61 | II-10 II-11       | 2001.9-2004.8        | 14                 | 27.39      |                     |
| W8-5      | 16 333 458.8 | 4 187 725.7 | II-9               | 2067.00-2069.10      | 11                 | 20.65      |                     |
| W6-14     | 16 336 522.8 | 4 186 753.7 | II-10 II-10 II-11 | 2006.70-2018.80      | 14.16              | 12.83      |                     |
| W5-17     | 16 337 310.8 | 4 186 530.7 | II-9 II-10 II-10 II-11 | 2025.00-2034.60   | 17                 | 23.92      |                     |
| W4-12     | 16 336 269.8 | 4 187 695.7 | II-9 II-10 II-11  | 2105.20-2115.30      | 17                 | 17.58      |                     |
| W4-15     | 16 337 177.8 | 4 187 176.7 | II-10 II-11        | 2060.00-2066.50      | 15.2               | 22         |                     |
| W7-7      | 16 334 229.8 | 4 187 675.7 | II-10 II-11       | 2030.60-2037.50      | 16                 | 21.26      |                     |
| W5-13     | 16 336 401.8 | 4 187 225.7 | II-10 II-11       | 2059.20-2064.10      | 16.5               | 22.66      |                     |
| W11-10    | 16 334 438  | 4 185 938  | II-7 II-8 II-9    | 2080.20-2093.30      | 16                 | 20.25      |                     |
| W6-16     | 16 336 839.8 | 4 186 574.7 | II-10 II-11       | 1999.4-2007.6        | 16                 | 18.87      |                     |
| W4-16     | 16 337 499.8 | 4 187 034.7 | II-9 II-10 II-10 II-11 | 2050.30-2063.60  | 17                 | 23.8       |                     |
| W4-14     | 16 336 871.8 | 4 187 356.7 | II-10 II-10 II-11  | 2067.60-2077.20      | 16                 | 23.64      |                     |
| W9-7      | 16 333 880.8 | 4 187 071.7 | II-7 II-8 II-9    | 2034.80-2048.90      | 17.1               | 20.54      |                     |
| W6-11     | 16 335 620.8 | 4 187 284.7 | II-9 II-10 II-11  | 2038.90-2048.00      | 17.5               | 23.85      |                     |
| W8-15     | 16 336 473.8 | 4 185 968.7 | II-7 II-11        | 1948.00-1974.80      | 32                 | 22.81      |                     |
| W6-10     | 16 335 313.8 | 4 187 446.7 | II-10 II-11       | 2052.70-2062.10      | 17.5               | 23.13      |                     |
| W8-6      | 16 333 759.8 | 4 187 549.7 | II-10 II-11       | 2054.90-2060.90      | 16.5               | 20.65      |                     |
| W6-6      | 16 334 090.8 | 4 188 141.7 | II-11               | 2143.70-2146.70      | 16.5               | 18.24      |                     |
| W3-13     | 16 336 755 | 4 187 828 | II-7 II-8 II-9    | 2101.00-2117.80      | 13                 | 19.42      |                     |
| W7-3      | 16 333 025.8 | 4 188 372.7 | II-7 II-7 II-8  | 2092.00-2107.7       | 17.5               | 20.83      |                     |
| W7-5      | 16 333 627.8 | 4 188 022.7 | II-7 II-7 II-7 + 8 | 2049.50-2061.80      | 17.5               | 25.12      |                     |

(Continues)
APPENDIX C  (Continued)

| Well name | X        | Y        | Fracturing horizon | Fracturing intervals | Proppant amount m³ | Sand ratio | Hydraulic fractures |
|-----------|----------|----------|--------------------|----------------------|--------------------|------------|---------------------|
| W6-18     | 16337 746.8 | 4186 082.7 | II II-9 II-11      | 2006.7-2020.4        | 15.5               | 20.49      | HF1 59.7 82.5 7 SE-NW144.8 |
|           |          |          |                    |                      |                    |            | HF2 65.3 75.5 9.7 SE-NW148.5 |
| W3-15     | 16337 342.8 | 4187 483.7 | II-5 II-8          | 2048.60-2078.00      | 17.5               | 22.14      | HF1 119.5 121.4 11.4 SE-NW162 |
|           |          |          |                    |                      |                    |            | HF2 65.3 75.5 6.4 SE-NW168 |
| W4-13     | 16336 580.8 | 4187 522.7 | II-13 II-17        | 2116.50-2159.30      | 13.5               | 20.9       | HF1 95.4 84.9 9.1 SE-NW152.1 |
|           |          |          |                    |                      |                    |            | HF2 93.8 95.1 10.9 SE-NW153.6 |
| W5-7      | 16334 587.8 | 4188 276.7 | II-10 II-11        | 2140.70-2149.20      | 14                 | 21.84      | HF1 71.6 73.5 15.2 SE-NW129.8 |
|           |          |          |                    |                      |                    |            | HF2 70.2 69.3 10.7 SE-NW138 |
| W10-13    | 16335 522.8 | 4185 717.7 | II-7 II-8 II-11    | 2096.50-2126.00      | 27.5               | 23.92      | HF1 70.4 74.3 11.7 SE-NW148.6 |
|           |          |          |                    |                      |                    |            | HF2 83.2 80.6 16.4 SE-NW154 |