A new method for identifying fractures in tight sandstone of a gentle structural area using well logs

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Abstract
In this paper, we conducted a systematic study on the development characteristics and logging prediction of fractures of the Upper Paleozoic tight gas sandstone reservoirs in the eastern Ordos Basin. A new fracture prediction method was proposed based on the variable scale fracture probabilistic model. The calculation steps of this method were as follows: First, the sensitivity of each conventional log series to the tight sandstone fractures was analyzed. It was found that acoustic time difference (AC), density (DEN), natural gamma ray (GR), and deep investigate double lateral resistivity (RD) have good log responses to fractures. Then, the ratio of the range (R) to the standard deviation (S) of the log data was obtained. Finally, the second derivatives of the log series AC, DEN, GR, and RD were calculated, and a new fracture index was constructed (integrated second derivative, $F_C$) using the multiple regression method. The fracture recognition rates of this method are distributed in 64.3%-85.7%. Therefore, the constructed integrated second derivative ($F_C$) based on conventional logs is effective to quantitatively characterize the fracture development of tight sandstone.

KEYWORDS
fracture; conventional logs, gentle tectonic zone, Ordos Basin, Upper Paleozoic strata

1 | INTRODUCTION
The Upper Paleozoic in the Ordos Basin contains abundant natural gas resources.1,2 The tight sandstone gas reservoirs inside the basin are a continuous gas accumulation.3,4 Tight sandstone generally refers to sandstone with porosity below 10% and overburden permeability below 0.1 mD.5 The continuous accumulation law makes the tight sandstone reservoir contain gas as a whole, but the productivity of each well often has a large difference, and the main influencing factors of the single-well productivity difference are sedimentary microfacies and fracture development.6-10 The presence of fractures can significantly improve the petrophysical properties of tight sandstone reservoirs and also provide an effective transport channel for the continuous filling of hydrocarbons from source rocks to tight sandstone reservoirs.7,11-19

Tight sandstone gas has a good development prospect; the study of fracture evaluation has drawn more and more
The fracture evaluation technology of tight reservoirs is based on the following three aspects: reservoir geological characteristics, rock physics, and geostress properties. The accurate identification of fractures can help people to better understand the contribution of fractures to fluid seepage, the evolution of fractures and its main controlling factors. Logging data have high vertical resolution, so it can be used to identify fractures. Prediction of fractures using well logs can accurately identify oil and gas sweet spots, thereby reducing exploration risks. The existence of fractures can often cause an increase in formation acoustic time difference, a decrease in density logging values, and a slight decrease in resistivity. Therefore, it is feasible to construct fracture models using conventional logs.

The variable scale fracture probabilistic model is an effective method for logging evaluation of fractures. It can predict fractures by extracting effective information from multiple log series and reducing the dimensions. Moreover, this method retains the initial information of the original data as much as possible. Based on this, in this paper, we conducted a systematic study on the development characteristics and the logging prediction of fractures of the Upper Paleozoic tight gas sandstone reservoirs in the eastern Ordos Basin, using outcrop profiles, cores, conventional logs, FMI image logs, and gas-testing results. This study has a positive significance for guiding the exploration of tight sandstone gas in gentle structural areas worldwide.

2 GEOLOGICAL BACKGROUND

The location of the study area is in the L block in the eastern Ordos Basin (Figure 1). It is in the intersection part of the Jinxi Flexural Zone and the Yishan Slope. The Upper Paleozoic strata in this area are relatively flat, and the structural fluctuation per 1 km of plane distance is generally <20 m. The Zijinshan Pluton (diapir magmatic rocks) is located in the southeastern region of the study area (Figure 1).

The sedimentary unit division of the Upper Paleozoic strata in the study area is shown in Figure 2. The Upper Paleozoic Carboniferous-Permian strata in this area develop typical marine-continental transitional facies sediments, including delta facies, river facies, and barrier coast facies. Among them, the Benxi and Taiyuan Formations are a set of barrier coastal sediments. During the sedimentary period of the Shanxi Formation, the sea receded and the strata gradually progressed into the delta plain facies.

The overlying Upper Shihezi, Lower Shihezi, and Shiqianfeng Formations are a set of extensive river facies deposition. Among them, the Upper Shihezi Formation
belongs to the braided river facies sediments, while the Lower Shihezi and Shiqianfeng Formations belong to the meandering river sediments.

The Ordos Basin is a large western inclined monoclinic. The Upper Paleozoic stratum is relatively flat, and the tectonic activity is weak. Under the condition of this structural background, the development degree of the fractures is relatively weak. Vertical and horizontal bedding fractures are mainly developed in the Upper Paleozoic strata.

TABLE 1  Distribution of the field survey locations

| Profile name          | Abbreviation | GPS coordinates          | The main exposed Upper Paleozoic strata                                                                 |
|-----------------------|--------------|--------------------------|-------------------------------------------------------------------------------------------------------|
| Zhunqi Heidaigou      | L1           | N: 39°24′17″, E: 111°16′24″ | Benxi Fm., Taiyuan Fm., Shanxi Fm., Shihezi Fm., Shiqianfeng Fm.                                      |
| Fugu Tianshengqiao    | L2           | N: 38°56′24″, E: 111°9′32″  | Taiyuan Fm., Shanxi Fm., Shihezi Fm.                                                                    |
| Ningwu Hongtugou      | L3           | N: 38°43′17″, E: 111°42′13″ | Benxi Fm., Taiyuan Fm., Shanxi Fm., Shihezi Fm.                                                        |
| Linxian Zhaoxianshui  | L4           | N: 37°35′25″, E: 110°52′57″ | Benxi Fm., Taiyuan Fm., Shanxi Fm., Shihezi Fm.                                                        |
| Puxian Heilongguan    | L5           | N: 36°9′26″, E: 110°58′32″  | Taiyuan Fm., Shanxi Fm.                                                                                |
| Hancheng Huangshuihe  | L6           | N: 35°28′34″, E: 110°24′3″  | Benxi Fm., Taiyuan Fm., Shanxi Fm., Shihezi Fm.                                                        |
3 | METHODS

3.1 | Fracture observation in outcrops and cores

The fractures were observed in 6 field outcrop profiles in the eastern Ordos Basin. The observation positions were L1-L6 (Figure 1). The coordinate positions of the 6 observation points are shown in Table 1. These observation points have typical exposures of the Upper Paleozoic strata. At least 30 sets of fracture data were observed at each observation point, and then, the formation occurrence, fracture groups, number of fractures, and fracture direction were described. The Zhunqi Heidaigou profile (L1) is located in the northernmost side with a formation inclination of 30° (Figure 3). The Benxi to Shiqianfeng Formations are well exposed (Table 1).

Core fracture observation and statistics were conducted on the Upper Paleozoic cores of 8 wells (Figure 1, Wells N1-N5, and Wells N8-N10). The observed core length is 102 m, and the fractures of the target layer were classified according to the genetic types. Meanwhile, the number and inclination of the fractures were counted.

3.2 | Fracture identification using FMI image logs

The fractures of Wells N1 to N7 were observed by FMI logs (Figure 1). FMI logs can effectively identify tight formation, mudstone, fault, bedding, cave, and natural fractures (Table 2). Meanwhile, the fracture observation results were continuous. Therefore, the fracture identification effects using FMI logs are significantly better than using drilling cores. The well segments with fractures generally present a significant dark sinusoidal image, and the fracture parameters generally display a high amount of abnormality (Figure 4). Since the cost of the FMI logs is very high, only some of the well intervals underwent FMI tests.

3.3 | Fracture probabilistic model

Two parameters, \( R \) (range) and \( S \) (standard deviation), were calculated using the variable scale fracture probabilistic model (Equations 1 and 2). Among them, \( R \) represents change in cumulative deviation, and \( S \) represents change in time series. Thus, \( R/S \) represents intensity of data fluctuation.

![Figure 3](image-url) The Upper Paleozoic outcrop in the Zhunqi Heidaigou profile (L1) in the eastern Ordos Basin. O is the Ordovician strata; \( C_2 b \) is the Benxi Formation; \( C_2 t \) is the Taiyuan Formation; \( P_1 s \) is the Shanxi Formation; \( P_2 x \) is the Lower Shihezi Formation; \( P_2-3 s \) is the Upper Shihezi Formation; and \( P_3 sh \) is the Shiqianfeng Formation.
TABLE 2  Response of geological body on FMI image logs

| Number | Geological body | Character          |
|--------|-----------------|--------------------|
| 1      | Tight formation | High resistivity bright segment |
| 2      | Mudstone        | Low resistivity dark segment |
| 3      | Fault           | Sinusoidal shape, but often appear in isolation |
| 4      | Bedding         | A stripe of dark and light. For a gentle structural belt, the bedding is near horizontal |
| 5      | Cave            | Black porphyritic |
| 6      | Natural fracture| Unfilled fractures are dark sinusoidal images; fully filled fractures are high resistivity bright colors |
| 7      | Drilling induced fracture | Appears at 180° or nearly 180° at the symmetrical position of the borehole wall |

The presence of fractures can cause fluctuations in the R/S curves.

\[
R(n) = 0 < \max \left\{ \frac{\sum_{i=1}^{n} Z(i) - \frac{1}{n} \sum_{j=1}^{n} Z(j)}{\sum_{j=1}^{n} Z(j)} \right\} - 0 < \min \left\{ \frac{\sum_{i=1}^{n} Z(i) - \frac{1}{n} \sum_{j=1}^{n} Z(j)}{\sum_{j=1}^{n} Z(j)} \right\}
\]

(1)

\[
S(n) = \sqrt{\frac{1}{n} \sum_{i=1}^{n} Z^2(i) - \left[ \frac{1}{n} \sum_{j=1}^{n} Z(j) \right]^2}
\]

(2)

where \( n \) is the number of logging data; \( Z \) represents a continuous time series; \( i \) and \( j \) represent each variable; and \( u \) is a data point from 0 to \( n \).

First, the R/S value of the target layer is calculated by the physical Equations 1 and 2. Then, the relationship between log(R/S) and log points (N) is obtained. The presence of fractures will cause a concave segment of the log(R/S) and logN curves.40

Relationship between log(R/S) and log(N) of Well N5 in the interval 1012-1300 m is shown in Figure 5. The variations in different types of logging parameters in Figure 5 have some differences. For example, the slope of the RD curve at M1 position has a significant decrease, while the slopes of the AC, DEN, and GR curves are not significantly reduced (Figure 5).

Pebbly coarse sandstone had developed at the M2 position, but there was no fracture here (Figure 5). The slope of the GR curve was significantly reduced, while the slopes of the AC, DEN, and RD curves were not significantly reduced (Figure 5).

Medium-fine-grained sandstone had developed at the M3 position, and fractures had also developed here. The slopes of the AC, DEN, GR, and RD curves all had a certain degree of reduction (Figure 5).

In order to effectively extract the position information of the concave segments, we have another derivation of log(R/S) and log(N) curves (or second-order derivation). If we define \( x_i \) be the curve of R/S and N, therefore, the first derivative results of \( x_i \) can be expressed as

\[
f'(x_i) = \left( \frac{\partial f}{\partial x} \right)_{x_i} \approx \frac{f(x_i + h) - f(x_i - h)}{2h}
\]

(3)

Then, the second derivative results of \( x_i \) can be expressed as

\[
f''(x_i) = \left( \frac{\partial^2 f}{\partial x^2} \right)_{x_i} \approx \frac{f(x_i + h) + f(x_i - h) - 2f(x_i)}{h^2}
\]

(4)

where \( h \) is the step size of any two adjacent logging data, and \( h = 1 \). We define \( K = f''(x_i) \). Therefore, when \( K < 0 \), the fractures do not develop, and if \( K > 0 \), the fractures develop.

4  | RESULTS

4.1  | Spatial distribution of outcrop fractures

Fracture is actually a three-dimensional entity that exists underground, and the drilling is only “a narrow view.” Therefore, quantitative characterization of fractures using outcrops can help us to obtain more effective information of fractures.41 The increase of single-well productivity of tight gas sandstone requires the maximum contact to fractures during drilling and fracturing. Clearly, the probability of a vertical well drilling a fracture is smaller than that of a horizontal well. Geometry of fractures has an important influence on the permeability anisotropy of tight sandstone reservoirs.
It was found that different degrees of fractures had developed in the upper Paleozoic tight sandstone through outcrop observation (Figure 6). In general, the probability of detecting a fracture in a vertical well can be generally expressed as the ratio of borehole size to fracture spacing. Therefore, for fractures with a spacing greater than the borehole size, conventional vertical wells most likely cannot detect them. Finally, the fractures observed in the outcrops were divided into three groups, as shown in Figure 6A-B. Type I fractures are nearly vertical fractures, which have the longest expanding distance and mostly cut along the long axis of the formation. The strikes of the fractures are mainly in the NW and NNW directions. Type II fractures are also high angle or nearly vertical fractures with relatively shorter expanding distances, which mainly cut along the short axis of the formation. The strikes of the fractures are mainly in the NE and NNE directions. Type III fractures are horizontal fractures. For the Type I and Type II fractures, the fracture spacing is relatively stable and appears as a uniform cutting of the matrix sand body.

Conjugate shear fracture is also common to see in the Upper Paleozoic tight sandstone in the eastern Ordos Basin (Figure 6C). Conjugate shearing structure is also called “X structure” or “hourglass structure.” For the upper crustal sedimentary rock masses, during the compression process, the formation of most conjugate shearing structures was accompanied by the horizontal structural extension and
strike-slip.\textsuperscript{46,47} For a given group of conjugate shear fractures, they generally intersect with each other at an acute angle. The sliding of the same group of fractures is usually considered as synchronous and isochronous.\textsuperscript{8,44} Sliding of this type of fracture will cause an increase or loss in the cross-sectional areas.\textsuperscript{48} The conjugate shear fractures shown in Figure 6C have small openings, straight fracture shapes, smooth fracture surfaces, and good directionality. Some fractures bend in its main extending direction. This is because, during the deformation of the strata, the compressive direction will change as well. Therefore, the fracture sliding phenomenon always appears in the low-amplitude tectonic zone.\textsuperscript{49}

The sand bodies in the subsurface generally have a lower fracture development degree than outcrops. However, for the fractures bearing fillings, there is almost no difference in the fracture opening degrees between these two types of sand bodies.\textsuperscript{50,51} Based on the field fracture observation results, the distribution of fractures was determined using the plane projection method (Figure 7).\textsuperscript{52} It could be found that there are steady strikes for the Type I and Type II fractures (Figure 7). In general, fractures have a specific strike, but, being affected by the superposition of multistages of tectonic movements, they may have several dominant strikes. Stable fracture strikes indicate that these fractures were formed in a unified tectonic stress field.\textsuperscript{53}
4.2 Fracture observation

The classification and proportion of fractures of tight sandstone in the target layers of the study area are shown in Figures 8 and 9A.

Tensile fracture is a type of structural fracture formed under tensile stress and have large openings and rough surfaces (Figure 8A). The proportion of tensile fractures in the target layers is 16.19% (Figure 9A).

Shear fractures are formed by structural shearing and are generally closed under strong formation stress conditions. Shear fractures are always straight and have a long extension scale (Figure 8B). They generally develop in groups, with a smooth fracture surface, and often cut through the rock particles. This type of fracture occupies the largest proportion of all fractures, accounting for 39.43% (Figure 9A).

Horizontal sliding fracture is also an important fracture type in the tight sandstone and accounts for 24.6% of all
fractures (Figure 9A). They were generally originated from the horizontal shearing along the bedding (Figure 8C). For regions where high angle or near vertical fractures are well developed, they will reach a “saturated” state. Then, the strain normal to the direction of these fractures (ie, the horizontal direction) will be absorbed by other types of deformation.54

**FIGURE 8** Core fractures images of tight sandstone. All cores were collected from vertical wells. A, Tensile fracture, Well N5, 1673.2-1673.5 m, He 8 segment; B, shear fracture, Well N5, 1610-1610.5 m, He 8 segment; C, horizontal sliding fracture, Well N6, 1610-1610.2 m, Shan 1 segment; D, squeeze fracture, Well N7, 1834-1834.1 m, He 8 segment; and E, dissolution fracture, Well N8, 1278-1278.3 m, He 2 segment

**FIGURE 9** Histogram of fracture type and dip distribution
In this case, interlayer sliding or interlaminar shearing failure will occur in the rock, which is an important reason for the formation of horizontal fractures.

Squeeze fracture was generally formed under the local strong compressive stresses when the compressive stress acting on the rock exceeds the rock’s own strength. This kind of fracture has a short extension, no fixed strike, and a disordered distribution (Figure 8D). The proportion of squeeze fractures is 6.42% (Figure 9A).

The proportion of dissolution fractures (Figure 8E) is relatively small. Dissolution can improve the effectiveness of fractures, and the proportion of this kind of fracture is 13.37% (Figure 9A).

Overall, the fractures in the target layer are mainly vertical fractures and followed by horizontal fractures (Figure 9B).

### 4.3 Fracture identification results using FMI logs

Fractures were observed in wells N1 to N7 via FMI logs. The fracture identification results of Well N3 are shown in Figure 10. It could be found that fractures were mainly developed in the Benxi, Taiyuan, and Lower Shihezi Formations.

The development degree of fractures in Well N3 increased gradually from the top to the bottom (Figure 10). Gas-testing tests were conducted on 4 gas layers in this well, and they were located in the He 4, He 5, He 6, and Tai 2 segments.

The gas-testing results of the He 4 segment showed that this gas layer had no gas production capacity, and fracture in this interval was not developed (Figure 10).

The gas production capacity of the gas-testing segment in the He 5 segment was 1000 m$^3$/d, belonging to a low-yield...
layer, which did not reach a commercial production capacity. Fracture in this interval was not developed as well.

The gas-testing production capacity of the He 6 segment was 2900 m$^3$/d, which was also lower than the commercial gas production capacity. Fracture in this interval was also not developed.

The gas-testing production capacity of the Tai 2 segment was 5000 m$^3$/d, which reached the commercial production capacity level. Fractures were mainly developed in the sand body at the top of the gas layer. Overall, the development of single-well fractures is related to the gas production capacity.

4.4 Fracture sensitivity of conventional logging parameters

The sensitivity of each conventional log series to fractures in the target layer was analyzed. The well log series analyzed included acoustic time difference (AC), resistivity, natural gamma ray (GR), density (DEN), and compensated neutron (CNL). Resistivity logs included deep investigate double lateral resistivity (RD) and shallow lateral resistivity (RS). RD can reflect the resistivity characteristics of the undisturbed formation, while RS is affected by the near-well flushing zone. Therefore, RD was selected for the fracture sensitivity analysis.

The distribution range of different types of logging parameters is shown in Table 3. AC and RD had better fracture recognition ability (Figure 11). It was found that AC of the fracture segment was mainly distributed at 57-77 μs/ft, with an average of 68 μs/ft and a standard deviation of 6.95; AC of the nonfracture segment was mainly distributed at 47-67 μs/ft, with an average of 58.9 μs/ft and a standard deviation of 6.17 (Figure 11). RD of the fracture segment was mainly distributed at 12-79 Ω·m, with an average of 36.6 Ω·m and a standard deviation of 48.1; RD of the

| AC (μs/ft) | DEN (g/cm³) | GR (API) | RD (Ω·m) |
|-----------|------------|----------|----------|
| Range     | Average    | Range    | Average  | Range    | Average  |
| 46-119    | 69.8       | 1.35-3.1 | 2.584    | 21-600   | 120.5    | 0.1-2000 | 103     |

FIGURE 11  Logging response of fractures in the upper Paleozoic tight sandstone of the study area
nonfracture segment was mainly distributed at 34-135 Ω·m, with an average of 71.8 Ω·m and a standard deviation of 16.65 (Figure 11).

For GR and DEN logs, since the fracture and nonfracture data are not significantly distinguished, we can conclude that the fracture identification ability of these two parameters is weak. That is, GR and DEN log series have a relatively weaker ability to identify fractures than AC and RD. GR of the fracture segment was mainly distributed at 46-130 API, with an average of 103 API and a standard deviation of 78.7. In some intervals in which vertical fractures were developed, the GR value had an increase (Figure 11A). The distribution of GR in the nonfracture segment was wide and was distributed between 47 and 180 API, with an average of 117 API and a standard deviation of 35.4 (Figure 11). DEN of the fracture segment was mainly distributed at 2.5-2.75 g/cm³, with an average of 2.65 g/cm³ and a standard deviation of 0.015; DEN of the nonfracture segment was mainly distributed at 2.64-2.85 g/cm³, with an average of 2.73 g/cm³ and a standard deviation of 0.096 (Figure 11).

Compensated neutron has a poor ability to identify fractures for tight sandstones in the target layer. There was no significant difference for CNL between fracture and nonfracture segments (Figure 11C).

Through the analysis of fracture sensitivity based on conventional logs, we found that RD, AC, DEN, and GR are sensitive to fractures. Therefore, these four parameters were selected for logging evaluation of fractures.

5 | DISCUSSION

5.1 | Construction of a new fracture index ($F_C$)

Based on the derivation of each log series, in this paper, the multiple regression method was used to extract effective information about fractures and achieve fracture prediction. The discrete value of the derivative result may originate from fractures, or originate from drastic changes in sedimentary facies or lithology. Therefore, using the multiple regression method to calculate the derivative data, on the one hand, can synthesize the effective fracture information of different log series; on the other hand, it can further improve the prediction accuracy of fractures. The calculation idea of this method is as follows:

1. First, we use the above Equations 1-4 to obtain the $K$ value of each log series ($K_{AC}$, $K_{DEN}$, $K_{GR}$, and $K_{RD}$);
2. Then, the multiple regression method was used to construct the fracture index $F_C$:

$$F_C = aK_{AC} + bK_{GR} + cK_{DEN} + dK_{RD} + e$$

when $F_C < 0$, the fractures do not develop, and if $F_C ≥ 0$, the fractures develop. The higher the $F_C$ value, the higher the development of fractures. The constant terms in Equation 5

FIGURE 12  Second-order derivative test of Well N3
were determined by multiple regression analysis. Then, the Equation 5 can be expressed as

$$F_C = 0.38K_{AC} + 2.6K_{GR} + 0.1K_{DEN} + 0.26K_{RD} - 0.02$$

$$R = 0.799.$$

Fracture identification is a typical nonlinear problem. In this paper, we first dealt with the four parameters $AC$, $DEN$, $GR$, and $RD$ based on the fracture probabilistic model, and this process is nonlinear. Although the processing results of these four parameters are inconsistent for the identification of fractures, however, they belong to the same level of parameters related to slope (or they are parallel parameters). Therefore, we only use a linear method to adjust the fracture recognition effect.

5.2 | Logging evaluation of fractures

The second derivative ($K$) of the 4 log series of Well N3 is shown in Figure 12. The $F_C$ had a threshold of 0.05 (Figure 13). A total of 12 fracture development intervals had developed in this well section, and eight of them were identified by the new fracture index. For the four gas-testing intervals (1406.6-1410.8 m, 1437.1-1441.5 m, 1485.4-1491.4 m, and 1702.2-1715 m), the recognition of the fracture segments was very good.

The fracture identification results from the 7 wells with FMI logs are shown in Table 3. The fracture recognition rate is distributed in 64.3%-85.7%, and the fracture identification effect is good.

5.3 | Relationship between fracture linear density and $F_C$

From the fracture logging prediction results of Wells N1-N7, the fracture identification rate using the new fracture index $F_C$ was between 64.3% and 83.3% (Table 4). For the main gas-testing layers, the fracture prediction results were very consistent with their actual distribution, indicating the effectiveness of this model.

Meanwhile, the relationship between $F_C$ and fracture linear density for the fracture intervals was analyzed, and the results are shown in Figure 14. There was a very good positive exponential correlation between the constructed $F_C$ and the fracture linear density. As the fracture linear density increased from 1 to 3 m$^{-1}$, the $F_C$ value increased from approximately 0.1 to 0.3.
5.4 Relationship between $F_C$ and gas well productivity

Based on the single-well fracture evaluation results and the gas-testing results, the coupling relationship between the open-flow productivity of single wells and $F_C$ was analyzed (Figure 15). The daily gas open-flow productivity per well of commercial gas wells in the study area is $>3000$ m$^3$. As can be seen from Figure 15, there is a positive correlation between $F_C$ and open-flow productivity. Factors affecting gas well productivity are multifaceted, including geological factors and engineering factors. Fracture is one of the geological factors, not the only factor.

As can be seen from Figure 15, when the $F_C$ value is greater than 0.55, most of the gas wells are commercial. However, there are two data with $F_C$ values below 0.55, but their daily gas production is more than 6000 m$^3$. The fractures in these two layers are not developed, but their petrophysical properties are very good, so the gas production is high. Through the research in this paper, it can be found that the fracture has a significant influence on the distribution of natural gas in tight sandstone reservoirs of the gentle tectonic areas in the Ordos Basin.

In this paper, we constructed a new method for identifying tight sandstone fractures in a gentle structural area using conventional logs. The original method uses only first-order derivation, while the method in this paper uses second-order derivation to identify fractures. At the same time, the method in this paper also couples multiple conventional logging parameters and establishes a quantitative relationship between $F_C$ and fracture linear density. The constructed integrated second derivative ($F_C$) can quantitatively evaluate the degree of fracture development. This study has a positive significance for the prediction of tight sandstone reservoir sweet spots in gentle tectonic areas worldwide.

6 CONCLUSIONS

1. Various types of fractures have developed in the Upper Paleozoic sandstone in the eastern Ordos Basin, and

| Serial number | Well | Discriminant accuracy (%) |
|---------------|------|---------------------------|
| 1             | N1   | 81.0                      |
| 2             | N2   | 71.4                      |
| 3             | N3   | 64.3                      |
| 4             | N4   | 76.2                      |
| 5             | N5   | 83.3                      |
| 6             | N6   | 70.0                      |
| 7             | N7   | 85.7                      |

**TABLE 4** Evaluation results of fractures in single wells

![Figure 14](image) Relationship between $F_C$ and fracture linear density

![Figure 15](image) Relationship between $F_C$ and open-flow productivity
FMI image logs were used to identify fractures. The results show that there is a close relationship between the fracture development degree and gas layer productivity.

2. In this paper, we constructed a new method for identifying tight sandstone fractures in gentle structural areas using conventional logs.

3. There is a very good positive exponential correlation between the fracture linear density and the constructed new fracture index $F_C$. $F_C$ can quantitatively evaluate the degree of fracture development.

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CONFLICT OF INTEREST
The authors declare no conflict of interests.

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