Sweet spots prediction through fracture genesis using multi-scale geological and geophysical data in the karst reservoirs of Cambrian Longwangmiao Carbonate Formation, Moxi-Gaoshiti area in Sichuan Basin, South China

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Abstract
Fractures play a vital role in reservoir transformation, but the distribution of faults and fractures is difficult to obtain by observing cores, which ultimately limits the effective development of gas dolomite reservoirs. We propose an integrated method that incorporates thin-section observations, three-dimensional (3D) seismic data, and image logs to interpret the distribution of faults and fractures of Cambrian Longwangmiao Carbonate Formation to predict potential development areas in the Moxi-Gaoshiti area of the Sichuan Basin, South China. Firstly, the faults were well interpreted by using the automatic tracking and 3D visualization technique based on the new seismic combination attribute of symmetry and ant tracking. Secondly, a comprehensive analysis was conducted using the thin sections, paleogeomorphology, and in situ test results to determine the fracture types (corrosion and structural fractures). The results help us to find potential sweet spot zones with good permeabilities, which is of great significance in reducing the risk of water production of drilled wells in the field development.

Keywords Fracture genesis · Sweet spot evaluation · Longwangmiao Formation · Moxi-Gaoshiti area · Sichuan Basin

Introduction
The gas reservoir of the Lower Cambrian Longwangmiao Formation (LWM Fm) in the Moxi area, Sichuan Basin, South China, is the largest mono-block gas field, with proven geological gas reserves of 4404 × 10⁸ m³ (Jin et al. 2014; Liu et al. 2014; Tian et al. 2015; Yang et al. 2015; Zhang et al. 2015). Intensive studies have been carried out on the accumulation conditions and enrichment patterns of the natural gas in this target formation (Du et al. 2014; Wei et al. 2015; Xu et al. 2014). The distribution of the dolomite reservoirs is controlled by structures, sedimentary facies, and karstification (Yao et al. 2013; Zhou et al. 2015; Zou et al. 2014). Previous studies have demonstrated that the porosity of granular beach facies is generally higher than those of the other facies (Jin et al. 2014; Liu et al. 2014; Tian et al. 2015; Yang et al. 2015; Zhang et al. 2015). A great deal of works have been done on the lithologic characteristics and the distribution of the granular beach facies in the vertical and lateral directions (Jin et al. 2015; Ma et al. 2015; Wang et al. 2017; Yang et al. 2015; Zhou et al. 2014a). The pore geometry of the reservoirs is complex, which can be classified into fracture-cavity type, fracture-porosity type, and intergranular pore type (Wang et al. 2019); and the corrosion fracture, cavities, and dissolution pores dominate the main storage space.

Natural fracture networks strongly control the hydrocarbon accumulation in tight carbonate reservoirs and play a vital role in improving reservoir permeability (Radwan et al. 2020a, 2020b). A wide variety of methods have been developed based on complex geological zone using well-logging data (Radwan et al. 2019, 2020c, 2021a; Ehsan et al. 2018, 2021; Ehsan and Gu, 2020). Many contemporary studies...

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have focused on identifying faults using advanced techniques (Riaz et al. 2019; Ullah et al. 2022). Recent studies have presented a workflow for characterizing faults and fractures using multi-source borehole data (Van Der Voet et al. 2020) and multi-attribute analysis (Ashraf et al. 2020a, 2019, 2021). Observations, descriptions, and statistical analysis of outcrops and thin sections in the field are the most direct and effective way to characterize fractures. Fractures can also be detected from conventional well logs and image logs with higher vertical resolutions (Ameen, 2014; Lai et al. 2018; Radwan et al. 2021b, 2021c). The method of core observation and logging interpretation can only provide information about the fracture features at the well site, whereas seismic data can provide information on the relative magnitude of the fractures in the lateral direction, but the fracture interpretation results of seismic data should be calibrated using core observations and logging interpretation results. Thus, in this study, we incorporated the 3D seismic data, well-log data, image logs, cores, and geology data (Anees et al. 2019; Ashraf et al. 2020b). In addition, the information from the literature regarding the fractures and faults was also incorporated to strengthen our results.

A substantial work was done on detecting faults and fractures based on conventional seismic attributes such as the dip and azimuth (Dalley et al. 2007), variance (Van Bemmel and Pepper, 2000), coherency (Chopra, 2002), and curvature attribute (Chopra and Marfurt, 2007) across various sedimentary basins. In recent years, new methods based on pre-stacked seismic data have emerged based on the principles of amplitude variation with azimuth (Chen et al. 2013; Zong et al. 2018), travel-time variation with azimuth (Craft et al. 1997), and velocity variation with azimuth (Al Dulaijan et al. 2016; Li and Others, 1997), and fracture proximity, thinned fault likelihood, and fracture density (Ashraf et al. 2020a). In our study area, we have employed post-stack data, thus we have extracted seismic attributes such as fracture proximity, thinned fault likelihood, and fracture density.

Each method provides fracture information on a different scale and has its own limitations. Thus, the research workflow was designed based on the available data to reduce the ambiguity of fracture detection. Previous investigations have focused on the characteristics and origin of the Sinian–Permian fault system and its control on the formation of paleo-carbonate reservoirs (Li et al. 2018a). However, very few studies have been conducted on fracture types identification and sweet spot evaluation (Li et al. 2014; Zhou et al. 2014b), which is vital for well-site design and field development planning.

A comprehensive study of the fractured zone is the key to a better assessment of the presence of hydrocarbons and geological trends for use in economic appraisals (Ashraf et al. 2016). Moreover, it is of great importance to the exploration of high-productivity gas wells. That is because fractures play a vital role in enhancing the permeability of reservoirs with the low matrix porosity property (ranging from 2 to 6% based on the logging interpretation). A better understanding of the pores complexity, faults, and fractures in Gaoshiti-Moxi area can lead to better understanding of pore characteristics (Mangi et al. 2020) and grain size analysis (Zhang et al. 2020, 2021a, 2021b), which in turn can be used to develop a rock physics model (Ali et al. 2020), hydrocarbon potential assessment (Anees et al. 2017; Abbas et al. 2019) and to evaluate the porosity (Ali et al. 2019, 2021). Nevertheless, highly developed fractures can also be related to the water production of drilled wells (Shahab et al. 2018). It is important to determine the fracture type and its distribution.

Former studies conducted on the Gaoshiti-Moxi area were related to the discussion of controlling factors of beach-controlled karst reservoirs (Mindong et al. 2014), karst paleogeomorphology (Mindong et al. 2017), depositional and diagenetic controls (Fu et al. 2020), hydrocarbon origin (Jin et al. 2016), and seismic prediction on the favorable efficient development areas (Zhang et al. 2017). However, studies regarding the fracture genesis and sweet spot evaluation in the Cambrian Longwangmiao Carbonate Formation, Moxi-Gaoshiti area in Sichuan Basin, South China, using multi-scale geological and geophysical data is still missing. Therefore, it is novel enough to integrate multi-scale 3D seismic, cores, thin section, image logs, and well-logging data to determine the fracture types and sweet spots which has significant meaning to deploy high gas production wells.

**Geological background**

The Sichuan Basin is a typical superimposed basin in South China, which covers about 18.8 × 10^4 km² (Fig. 1a). It underwent various structural movements, including the Yangtze, Xingkai, Caledonian, Hercynian, Indosinian, Yanshanian, and Himalayan tectonic cycles (Liu et al. 2013). The Sichuan Basin and its surrounding tectonic belts have undergone multi-stage tectonic superimposition and transformation (Chang et al. 2017). The distributions of the orogenic belts and the stress fields have a tremendous effect on the distribution of faults and fractures. The Moxi-Gaoshiti area is situated in the central part of the Sichuan Basin with extremely steep fault zones. The Lower Cambrian LWM Fm is a carbonate formation in which the primary deposits are pure dolomite. The thickness of the LWM Fm in the study area ranges from 50 to 120 m.

The accumulation of the hydrocarbons in the complicated stratigraphic and structural traps within the carbonate reservoirs of the LWM Fm and the Upper Sinian Dengying Fm was created by the Sinian–Permian extensional fault system (Du et al. 2015). The lithofacies of the LWM Fm consist of thickly bedded gray dolomite, intercalated with...
shaly dolomite at the top and limestone at the bottom (Du et al. 2015) (Fig. 1c). Greater dissimilarities and transformations occurred in the interbank sea deposits and the grain bank deposits of the gentle paleo-carbonated ramp during the deposition of the LWM Fm. The robust movements on the NE striking faults and the rapid deposition of the grain
bank facies occurred on the hanging wall of the NE striking strike-slip fault rather than on the NW striking strike-slip fault of the Moxi paleo-uplift (Du et al. 2015). The Moxi-Gaoshiti paleo-uplift was deposited during the Tong-Wan movement during the Late Sinian. A restricted platform controlled the reservoirs in the Gaoshiti-Moxi area. Most of the reservoirs were developed in the upper and middle parts of the LWM Fm, and the fracture zones could improve the permeability of these reservoirs. The matrix porosity of the LWM Fm is extremely low, and the fractures could play a crucial role in enhancing the hydrocarbon production.

Dataset and methods

Datasets

A 3D pre-stacked time migration dataset covering 1500 square kilometers in the study area was used in this study (Fig. 1b). More than 50 wells have been drilled in the LWM Fm. Most of these wells have conventional logs, but only a few wells were run with unconventional logs such as array acoustic and image logs. The fracture descriptions and observations were conducted based on 200 m of core, thin sections from 28 cored wells, and image log data from 13 wells.

Methodology and workflow

The workflow adopted in this study is shown in Fig. 2. In the first phase of the research, we have employed the structural smoothing and data conditioning using structural filtering to sharpen the structural discontinuities within the study area. In this dataset, symmetry and ant tracking algorithms were combined to identify structural discontinuities, such as major and minor faults. The geometric attributes, such as the curvature, fracture proximity, fracture density, and the maximum likelihood attribute (MLA), were also computed to confirm the presence of the fractures. In addition, 3D visualization and automatic tracking were conducted to interpret the faults and horizons. Furthermore, the fracture zones were characterized using MLA. In the second phase of the study, integrated analysis was performed using the core, thin section, and image logs to delineate the orientations of the fractures. These results were correlated with the results of the seismic attribute analysis for fracture detection. In the final phase of our study, the genesis of the fractures was comprehensively analyzed integrating geological data and seismic attribute to determine fractures type and sweet spot that can be further exploited for future prospect evaluation and for potential exploration in our study area.

Conditioning of the 3D seismic data

The first step of the seismic interpretation was to perform the data conditioning on the seismic data to enhance and sharpen the continuous structural discontinuities. In this step, various structural filters and structural smoothing were applied to reduce the random noise (Fig. 3). The goal of this step was to enhance the continuity of the seismic phase and to improve the accuracy of the fault identification.

Results

Attribute analysis for fault interpretation

Symmetry

Symmetry is a fundamental attribute in human visual perception as well as in many natural structures (Nixon et al. 2014). Symmetry analysis is a new type of seismic volumetric attribute used to measure the degree of chaos in seismic data, which is sensitive to the seismic amplitude variations. Therefore, it strongly correlates with the discontinuities and curvatures associated with imaged geological surfaces. According to the linear system theory, linear transformation does not affect randomness (Lawther et al. 2016). If the seismic reflection coefficient sequence is regarded as a generalized Gaussian input signal, the output seismic trace should be the same as the distributed stationary signal, where the seismic wavelet is considered to be the transmission function of the
system (Caine et al. 1996). However, when a subsurface feature such as a fault, channel, or fracture-cavity in a carbonate area undergoes transverse mutation, the seismic data will follow the asymmetric generalized Gaussian distribution. Thus, the mutation area can be identified using this phenomenon.

The slope and kurtosis of random signals are two essential parameters of non-asymmetric and non-Gaussian distributions, respectively. The slope and kurtosis are defined as in Eqs. 1 and 2, respectively:

\[ S = \frac{E(x - \mu)^3}{\sigma^3} \]  
\[ K = \frac{E(x - \mu)^4}{\sigma^4} \]

where \( S \) is the slope; \( K \) is the kurtosis; \( x \) denotes the time series; \( \mu \) is the mean value; \( \sigma \) is the variance; and \( E \) is the mathematical expectation. Under the condition of the standard normal distribution, the slope and kurtosis of the time series are 0 and 3, respectively. We defined the change rate of the slope and kurtosis relative to the entire formation to detect the non-asymmetric and non-Gaussian properties of the seismic signals, as shown in Eqs. 3 and 4, respectively:

\[ X_S(n) = \frac{S(n) - S}{S} \]  
\[ Y_K = \frac{K(n) - K}{K} \]

where \( S(n) \) and \( K(n) \) are the slope and kurtosis at time \( n \), respectively; and \( S \) and \( K \) are the slope and kurtosis of the entire seismic trace, respectively.

Using this method, the non-asymmetric and non-Gaussian changes of the seismic signals can be characterized more precisely (Yin et al. 2018). Compared with other geometric attributes, this method can more effectively reveal subtle changes through a waveform comparison with the adjacent seismic trace (Fig. 4a).

**Ant tracking**

The ant tracking attribute was used to perform automatic analysis and recognition of the fracture systems. The ant tracking algorithm is based on the idea of ant colony systems and is used to capture trends in noisy data. Intelligent agents trace or extract discontinuous features, such as coherency in an edge-detection volume. This approach enhances the discontinuities in an edge-detection volume because it only captures the features that are discontinuous and are likely to be faults. This method is widely used to identify faults and fractures on the seismic scale (Ma et al. 2014; Wang et al. 2013; Zhuang et al. 2018).

The faults in the study area are characterized by small fault displacements. Thus, conventional coherence attributes cannot produce a clear fault image. The integration of the symmetry attribute and the ant tracking method has a better ability to detect the edges of faults (Fig. 4b). By combining the results of the fault detection slices with the interpretation results of the profile, the quality of the fault interpretation is controlled in 3D space to interpret the faults in a more precise and reasonable way (Fig. 5).
Similarity

Similarity is a structural attribute, and is a type of coherency attribute. The range of similarity attributes lies from 0 to 1. The similarity attributes show the similarity of the structural features that are continuous (Tingdahl and de Groot, 2003). The similarity is a semblance-based attribute that is used for the assessment of dips having maximum semblance chosen for that dip (Marfurt, 1998). The results of the similarity attribute were applied to display and analyze the coherency across seismic cube. The similarity attributes were applied using the fault enhancement filter (FEF), because the similarity attribute is very sensitive toward noise. Initially, dip steering was calculated for the calculation of the FEF and then similarity was applied on the FEF seismic cube. The FEF improves the accuracy and enhances the sharpness of the continuous structural features such as faults. The results of FEF similarity were analyzed on the maps to identify the major structural discontinuities. Since the similarity attribute was unable to identify the minor structural discontinuities, therefore, we applied the thinned fault likelihood attribute (TFL) (Fig. 6a).

Thinned fault likelihood (TFL)

The thinned fault likelihood (TFL) attribute is an advanced unconventional attribute that is developed by Colorado school of mines. The TFL is described as power of semblance. The range of the TFL lies from 0 to 1 and TFL extracts the seismic cubes with razor sharp edges. The TFL identifies the dips of the faults to measure the maximum likelihood to demarcate the faults and fractures in the targeted area and provide razor sharp edges of the maps (Hale, 2013). The results of the TFL show better results than curvature and similarity attributes as it was able to identify the minor structural discontinuities which are more visible on the TFL map (Fig. 6b).

Attribute analysis for fracture interpretation

Curvature

Curvature is a geometric attribute that measures the degree of bending of a structure. Curvature is an efficient geometric attribute for the detection of minor and major faults and...
fractures with very low displacements that are very difficult to recognize using other structural attributes such as coherency. The curvature attribute assumes that the structure of the horizon is a quadratic surface (Roberts, 2001). Many curvature attributes were computed, which incorporated the most positive curvature, the most negative curvature, the

Fig. 5  a Fault interpretation of the combining attribute slice; b fault quality control on the 3D space; and c seismic profiles perpendicular to the fault’s strike. The location of the section is represented by random line A–B in Fig. 1b

Fig. 6  a FEF similarity attribute showing the major structural discontinuities and b TFL highlighting the minor and major structural discontinuities of the study area
maximum curvature, and the minimum curvature. The result of the most positive curvature was more helpful in identifying the maximum structural discontinuities (Fig. 8a).

**Maximum likelihood attribute (MLA)**

The maximum likelihood attribute (MLA) was used to identify fractures using post-stacked seismic data, and it was generally used to automatically extract fault surfaces as meshes of quadrilaterals that coincide with the ridges of fault likelihood (Hale, 2013). The process of the method was as follows: First, we calculated the coherency coefficient at different fault dips $\theta$ and strikes $\phi$, and then, we took the maximum value from Eq. 5 as the MLA. This attribute is widely used to identify strike-slip faults and fractures taking into account the effect of the dip and strike (Harris et al. 2019; Ma et al. 2019).

The MLA is defined as:

$$\text{Maximum likelihood (x, y, r)} = \max [1 - C(x, y, r, \theta, \phi)^n]$$

where $C(x, y, r, \theta, \phi)$ is the coherency coefficient at different fault dips $\theta$ and strikes $\phi$; and $n$ is a given constant.

Compared with the curvature attribute, the fracture detection results obtained using the MLA are more consistent with the fracture density results observed in the core samples (Fig. 7) and from the in situ tests. In Fig. 8b, the blue area represents a higher formation permeability near wells 13 and 17, and the white to gray areas represent from the most positive curvature attribute overlapped by the interpreted faults and b fracture detection results from the MLA overlapped by the interpreted faults.

![Fig. 7](image_url) 
**Fig. 7** Plot of curvature and fracture density (left side) and MLA versus the fracture density of core observations (right side)

![Fig. 8](image_url) 
**Fig. 8** Fault and fracture system superimposed on the well test chart (the magenta chart represents daily gas production and the blue one stands for daily water production). a Fracture detection results from the most positive curvature attribute overlapped by the interpreted faults and b fracture detection results from the MLA overlapped by the interpreted faults.
lower formation permeabilities such as near well 203. The correlation coefficient between the MLA values and the fracture density results from the core samples is higher than that for the curvature attribute. Thus, the MLA indicates the fracture density more effectively. In addition, the fracture detection results were validated using multi-scale data such as thin sections, core observations, and image logs. Taking well 13 as an example, the thin sections, core observations, and image logs reveal that the formation contains fractures, which agrees with the MLA results.

According to the statistics of the image logging data (Fig. 9a–d), the main fractures in the formation have a NE to W–E strike, which is also consistent with the MLA results.

The other type of fracture development zone strikes SE (red arrow in Fig. 8b). There is no large-scale fault in this direction. The MLA attribute shows that small dense fractures developed. The characteristics of the seismic profile are as follows. There are no faults on the profile, and the corrosion fractures developed along the seismic event with abrupt lateral changes in seismic amplitude, reflecting changes in the reservoir porosity and permeability (red arrow in Fig. 10), but the structural fractures developed along the fault (blue arrow in Fig. 10).

We also studied the characteristics of the two fracture zones through the comprehensive analysis of thin sections, well logs, and paleogeomorphology. The thin section shows that the pore space is dominated by corrosion pores and fractures; Fractures can be subdivided into structural fractures and corrosion fractures. Because the genesis of structural fracture and dissolution fractures are different, they can be distinguished morphologically under the thin section. Structural fracture is controlled by tectonic stress. Therefore, it often cuts through various rigid particles (dolomite particles), and the shape of fracture is narrow and long (Fig. 11 a–b). The corrosion fracture is formed due to the dissolution of minerals. Therefore, the fracture shape is wider than structural fractures, but the extension length is limited, which is often limited to a certain range (Fig. 11 c–d). In addition, there

Fig. 9 Image logs and rose diagrams of well-13
is an obvious asphalt filling difference between structural fracture and corrosion fracture in the study area. Due to the relatively large corrosion fracture and high oil filling degree in geological history, the asphalt filling degree in the dissolution fracture is higher. Moreover, based on the core observations and image log data analysis, the fractures are characterized by high inclination angles ranging from 70° to 80° and NW to near E–W and NE strikes (Fig. 12 a–b).

Fracture density

Fracture density is a novel seismic attribute that displays the zones of maximum possibility of fractures (Ashraf et al.)
The fracture density attribute is described as the ratio of traces numbers which are classified as fractures divided by the total traces numbers in a given radius along slices. This attribute is helpful in highlighting the fractures zones of high density. The regions of high dense fractures can be exploited for future drilling prospects since the zones of high fracture densities are more conducive than low fracture densities. It also represents the improved imaging of potential fracture anomalies. The results of the fracture density show that the study area has high fracture densities at NE and SE regions. The SE region of the study area has no drilled well, and the fracture densities are quite high in those regions which is highlighted by black color. Since high fracture density regions are more conductive, therefore, these high dense fracture zone is sweet spot zone and can be exploited for future drillings (Fig. 13a).

Fracture proximity

Fracture proximity attribute is an unconventional advanced attribute that is applied for the identification of regions of high fracture activities in a given radius (Ashraf et al. 2020a). It calculates the horizontal distance from a given trace position that is described as a fracture. It is also quite beneficial for exploiting the radius for future drillings. The fracture proximity attribute computes the distance from the
center of the fracture. The results of the fracture activities show that the maximum area of the study area is affected by fracture activity regions. The results of the fracture proximity are consistent with the results of the fracture density. The NE and SE regions are represented by maximum activity regions (Fig. 13b).

Discussion

Distribution of fault and fracture in Moxi-Gaoshiti area

The results show two major types of fault-fracture zones in the central Sichuan Basin. The first type of fracture zone consists of E–W striking faults and fractures near the faults (blue arrow in Fig. 8b). This group of faults exhibits the following characteristics: the fracture development zone is relatively limited, and the strikes of the fractures are basically the same as those of the faults. These strike-slip fault patterns are steep and vertical with Y-shaped and reversed Y-shaped flower structures (Ma et al. 2018).

A total of eleven major faults were separately identified based on the fault interpretation patterns obtained by using a combination of symmetry and ant tracking attributes under the guidance of the fault interpretation patterns. These faults are mainly strike in NE direction, followed by NW direction. The deep faults are horizontal strike-slip faults, which are characterized by long extensions in the horizontal direction and small fault displacements in the vertical direction.

Implication of fracture types and their characteristics

The structural fractures have strike-slip shear features and NW to near E–W strikes, which are consistent with the major fault predicted using the MLA (Fig. 8b). According to previous studies, this group of faults is a fault-fracture system formed by the later tensile and torsional stress environment (Yin et al. 2013). The deformation during this period not only caused the development of tensile-torsion faults but also created fractures with the same characteristics and strikes within the stratum. This type of fracture can immediately connect the edge water and bottom water close to the faults at locations such as those of well-42, well-27, well-7-H1, and well-47 during hydraulic fracturing (Fig. 8b). Wells drilled in the proximity of this type of fracture experienced water production during the in situ tests. Therefore, when optimizing well locations, well sites distant from this type of fracture should be chosen.

Corrosion fractures are well developed in well-13. Well-13 is located in the SE striking fracture development zone predicted using the MLA. It shows that the SE striking fracture development zone reflects the distribution
of corrosion fractures. The formation of the corrosion fractures is controlled by the paleogeomorphology of the study area. The LWM Fm reservoir is composed of grain banks and karst, and thus, it is a composite grain bank and karst reservoir. Two factors entirely determine the reservoir's properties: the first one is the sedimentation of the grain bank, and the second one is supergene karstification, which is mainly controlled by the paleogeomorphology. From a paleo-geomorphologic viewpoint, the paleotopography can be classified as karst highlands, karst slopes, and karst depressions. The karst highlands and karst slopes are the most promising facies belts for karst reservoirs, which help to generate fractures related to karstification.

The paleogeomorphology during the final stage of the sedimentation of the LWM Fm was recovered from the seismic data based on the residual thickness of the interpreted horizon (Zeng et al. 2018). The formation thickness from the bottom of the Permian system to the top of the LWM Fm can be used to determine the geomorphology. It shows the zone with the thinner thickness is the highland (Fig. 14b), the paleotopography was higher in the west than in the east, and a NE striking slope zone was developed in the central part of the study area. The strike of the fracture zone predicted using the MLA is consistent with the strike of this slope zone. This type of fracture is related to dissolution and can dramatically improve reservoir permeability, such as for well-13, well-17, well-21, and well-204 (Fig. 14a). Therefore, it is inferred that new wells can be deployed based on the paleogeomorphology and fracture detection results to drill in the wells in those sweet spot zones, where the corrosion fractures are well developed but faults are absent, so that the risk of producing water from the well can be avoided.

**Conclusions**

We have presented a workflow to identify the fracture type by integrating the geological and geophysical data, and the result was verified using thin sections, core observations, image logs, and in situ test results. By making full use of the high-resolution 3D seismic data, the faults were delineated through a combination of the symmetry and ant tracking attributes. One of the most significant findings of this study is that the likelihood attribute, TFL, fracture density, and fracture proximity can be used to precisely characterize fractures due to its excellent fracture detection ability.

Two types of fracture zones developed in the study area: fractures generated through structural movement and the ones produced by corrosion. A comprehensive analysis of the fractures, structures, and paleogeomorphology reduces the ambiguity of the fracture prediction resulted from the seismic data. By integrating in situ drilling tests, we precisely determined that the critical factor for high-production wells is the corrosion fractures formed in the paleo-geomorphologic slope zones. During well location deployment, priority should be given to the sweet spot zones containing corrosion fractures.
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Data Availability  The well and seismic data used to support our findings have not been made available because the data used in this paper have not been approved for public use.

Declarations

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

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