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Characteristics of Rupture Development and Prediction Methods in the Central Sichuan Basin, China

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Abstract: Middle and deep faults are developed in the Sichuan Basin-Chuanzhong area, and the spatial structure of the faults is divided into three parts: fault core, fracture zone, and induced fracture zone. The fracture zone is the fracture space formed when the rock is crushed by more than the strength limit stress, the fault core is the area which is filled with muddy and small rock fragments in the late stage of the stress damage at the center of the fracture zone, and the induced fracture zone is the area developed when the surrounding rock is affected by the stress on the two sides of the fracture zone. The induced fracture zone is the area where a large number of fractures are developed in the surrounding rocks on both sides of the fracture zone under the influence of stress. The study shows that the carbonate fracture zone is a favorable part for the development of reservoirs with seam and hole bodies, and the identification and prediction of fracture development zones are of great significance for the selection of oil and gas well locations. From the core of the fault, the fracture zone to the induced fracture zone, from the core to the outside, the difference in the degree of fracture development causes changes in logging and seismic response characteristics, such as the gradual decrease of natural gamma/neutron, the gradual increase of density/velocity/resistivity value/permeability, and the seismic data amplitude weakening, frequency increasing, and waveform changing. This paper makes use of log data interpretation, seismic attribute preference, multi-attribute fusion, and fracture-solution inversion to form a set of technical series for identifying fracture zones by geophysical methods, which will lay the foundation for the next step of fine prediction demand for exploration and development in the central Sichuan area.

Keywords: Sichuan Basin; Fracture structure; Transport channel; Logging response characteristics; Seismic response characteristics; Seismic attribute preference; Rupture solution inversion

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1. Introduction

The fracture zone is mainly composed of fault core, broken zone, and induced seam, 3-part combination of three-dimensional seam structure. When the stratum is subjected to more than the strength limit of the stress, it leads to the rapid expansion of the concentration of primary pore volume in the stratum, the stratum occurred in the formation of the fault surface fracture effect. When the stress on the two discs above and below the fault plane exceeds the frictional resistance of the strata, the two discs of the strata will slide relative to each other. The two discs of the strata are deformed and damaged by the frictional sliding of the strata due to the stress, and the two discs of the strata are fractured by the deformation and destruction of rocks. At the same time, the two discs of the strata, fine rock fragments and mud, will fill the expanding pore space to form a fracture zone, and the greater the stress in the central part of the fracture zone, the longer the duration, leading to more development of the suture holes in the late stage of the formation of the fracture core by mud, small rock fragments and completely filled. The latter is filled with mud and small rock debris to form the core of the fault. At the same time, the surrounding rock near the fracture zone is also subject to stress, forming a large number of network cracks in the transition zone between the fracture zone and the intact rock, i.e., the induced fracture zone. The induced fracture zone is located in the local space on both sides of the fracture zone, in the vicinity of the main rupture is affected by the stress, the size and density of the network cracks is also large, with the distance from the center of the fracture zone gradually increased, the cracks are developing more and more small, until completely disappeared [1–2].

Fracture mainly follows the evolution process of activity-quiescence-re-activity-quiescence, and fracture activity is easy to form dominant fissure channels inside the formation, oil and gas transport along the fracture zone in large scale, so the dominant fissure during the period of fracture activity is the dominant channel for oil and gas transport along the fracture zone, and induced fissure is the second most connectivity. After the fault activity stops, the fault mud inside the fracture zone under the pressure of the overlying rock layer will quickly fill up the dominant fissures, lose their permeability, and become closed, and the induced fissures are the main channels for transporting hydrocarbons. Fracture throughout the entire process of gas reservoir formation is the communication between the gas source, the main channel of oil and gas transport, and the oil and gas reservoirs have a close relationship [2].

The gas reservoirs in the middle and deep carbonate rocks in the central area of Sichuan Basin are the main fields for oil fields to increase the storage and production, and a lot of research has been carried out for the gas reservoirs in the carbonate rocks of Permian, Cambrian, and Aurignacian systems, and fruitful results have been achieved. The Aurignacian-Permian period in the central Sichuan area was affected by three phases of tectonic movement to form a multi-phase fracture system, in the Aurignacian system by the Tongwan I, II curtain role of the influence of the Lamp II, Lamp IV section of the internal fracture development, Lamp IV section, the Permian system experienced short-term uplift exposures, did not form large-scale unconformity, epigenetic karst is weaker, and the development of internal fracture. In recent years, with the deepening of exploration and development in the central Sichuan area, many exploration wells and development wells deployed around fractures in the Gaoshitian and Longniesi areas have obtained high-yield industrial gas flow, and six high-yield horizontal wells have been drilled through the fracture broken zone of the Permian system, which has led to the gradual recognition that fracture development zones contain rich oil and gas resources, and moreover, they are the basis for high-yield wells in the central Sichuan area [3].

In conclusion, the fracture crushing zone is a deformation zone of seam and hole development, up to several kilometers wide in the central Sichuan area, which is the main area of reservoir development and fluid action, and the main channel for oil and gas transport. The study area is dominated by strike-slip fractures, with small longitudinal displacements, limited subsurface data, fewer fractures encountered in downhole drilling, difficult logging identification, and difficult identification of fracture zones. The previous research mainly focuses on geological model research and seismic attribute prediction, through the comparative analysis of seismic methods and techniques, using a variety of seismic attributes to carry out fault fracture zone research, qualitative identification of the distribution of fracture zones, as well as to carry out the research on the role of fractures in the control of reservoir formation and distribution [1, 4–5]. The above studies focus on analyzing the role of fractures as a whole in controlling storage and reservoir control, and there is no research on the identification of different spatial structures of a fracture and comparison of hydrocarbon transport capacity, which results in the inability to explain that near the same fracture, there are some areas rich in hydrocarbons and some areas poor in hydrocarbons, and the difference in the yield of a single well is obvious and so on, which undoubtedly limit the efficient and accurate exploration and development and deployment process of the fractured pore-type reservoirs. These problems undoubtedly limit the process of efficient and accurate exploration and deployment of fractured porous reservoirs. Therefore, it is necessary to carry out a fine portrayal of the spatial structure of fracture zones, analyze and study the differences in oil and gas transport to provide a reliable basis for oil and gas reservoirs and guide the deployment of wells.

The Aurignacian-Permian carbonate gas reservoirs in the central Sichuan Basin are a major challenge for oilfield exploration and development, and the gas reservoirs are mainly concentrated in the vicinity of the fracture zones, and the fractures have internal structural differences that affect the formation and development of the gas reservoirs, so understanding the petrophysical characteristics of the fracture zones lays a solid data foundation for finding the advantageous reservoir development areas. In this paper, the authors analyze and study the types and characteristics of fracture zones in carbonate gas reservoirs in Sichuan Basin by integrating core, thin-section analysis, logging and drilling data, summarize the petrophysical response characteristics of fracture zones, and explore the method of identifying the distribution pattern of fracture zones by geophysical methods, which is of great significance for understanding the formation mechanism of high-yield gas fields.

2. Geological background

The central Sichuan area is located in the east-central part of the Sichuan Basin's Gaomolping Gently Tectonic Belt, with the overall monoclinic tectonics of low north and high south, and the main purpose layer is the greywacke of the Upper Permian Maokou Formation and Qixia Formation, with a thickness of about 400 m, and the depth of carbonate reservoirs is at 4,500–5,000 m.

In the middle and deep layers of the study area, near east-west oriented strike-slip fractures are mainly developed, which are mainly distributed in the Permian-Aurignan carbonate rock strata; the secondary fractures are mainly oriented in the north-east direction, which are mainly distributed in the Permian strata. The primary strike-slip faults are mainly inherited high and steep upright, flower-like main faults, concentrated in the north-central part of the study area, and a series of geolithic tectonics are developed along the east-west oriented primary strike-slip fault zones, which form graben tectonics distributed in a near-north-south direction [7].

The Permian peripheral rocks in the study area are mainly greywacke, and the thin dolomite reservoirs of fracture pore type are developed in the middle and upper parts of the study area, which are distributed along the fracture zones within a range of 10 km, and are mainly concentrated in the fault fracture zones. The study area is rich in gas resources, with a gas-bearing area of 4,200 km^2 at the exploration site, mainly distributed near the fracture zone system (**Figures 1** and **2**).

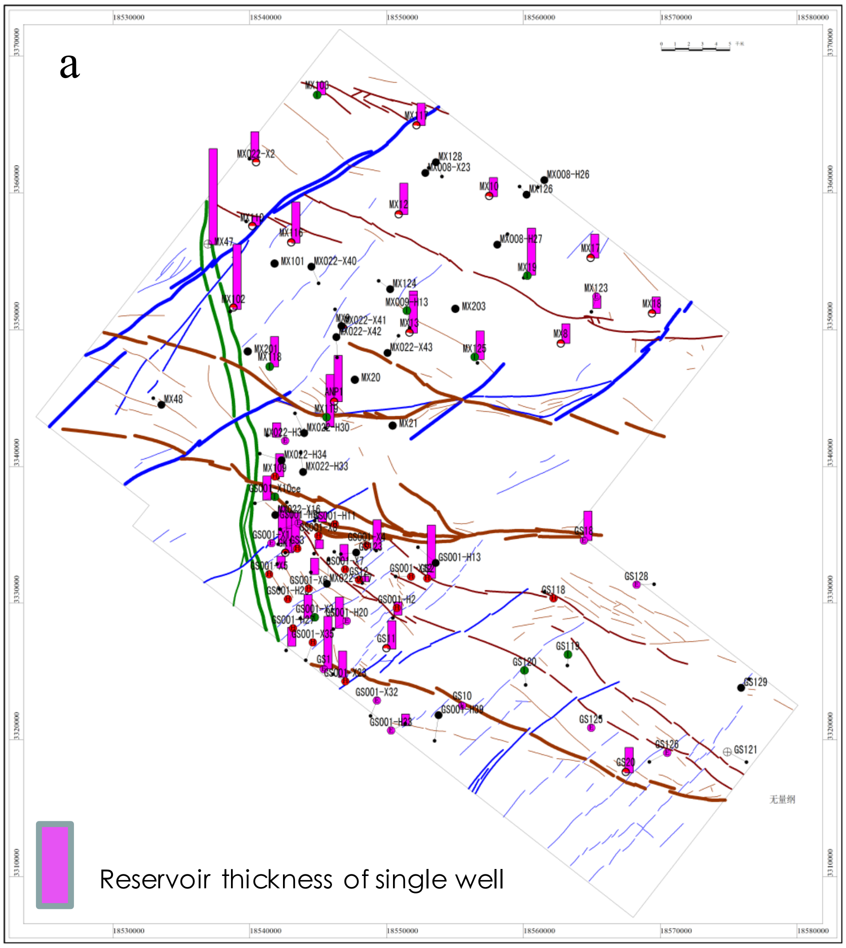


Figure 1. Overlapping production data chart of the fault system in the Gaomo area

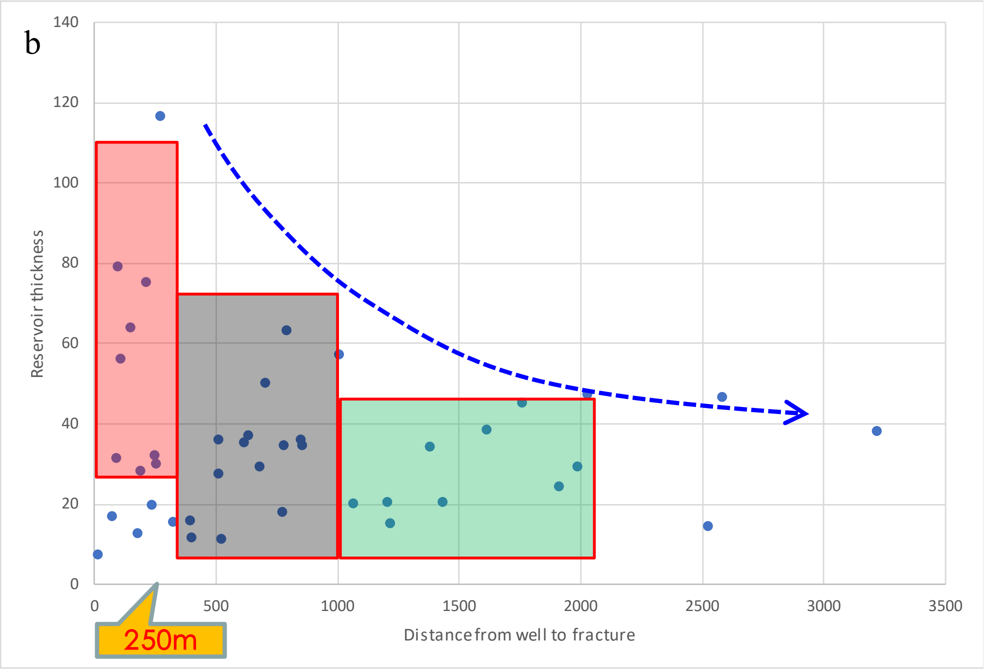


Figure 2. Intersection diagram of well to fault distance and reservoir thickness

3. Rock physical characteristics of crushing zones

The Permian in the central Sichuan Basin has a wide fracture zone, which is significantly different from the surrounding rocks in terms of lithological assemblage and physical size. The study area is rich in logging, seismic, and core data, including conventional three porosity curves, resistivity, and lithology curves, and special project logging including imaging logging and far-detecting acoustic logging, and the latest high-resolution seismic data have been collected. Each kind of logging curve can reflect the distribution of fractures in the formation to different degrees, only the physical significance and sensitivity of different logging curves are different; different seismic attributes extracted also react to the distribution of fracture zones to different degrees. Through the well one seismic calibration, combined with the geological characteristics of the target formation in the study area, useful fracture response information is extracted, and it is found that the response characteristics of the fracture differ significantly, and different geophysical response characteristics from the surrounding rock can be identified (**Figure 1**), which can further delineate the spatial distribution of the fracture zones.

3.1. Logging response characteristics

The logging response characteristics table and gas test results of the fracture zone, summarized with a total of six horizontal wells drilled through the fracture zone in the study area, indicate that the fracture zone is the main gas-producing section. One of the horizontal wells, Mill Creek 127, drilled through the dolomite reservoir, penetrated the fault horizontally (**Figure 3**). Using the core and imaging log data to calibrate the conventional logs and analyze the fracture characteristics, fault breccia and colluvial fillings of mud (presumed to be fault mud) and siliceous material were observed at the core location of the fracture zone (logging depths of 5706–5707 m) (**Figure 3**), which is very significant compared with the response of imaging logs of the layers shallower than 5706 and deeper than 5707 m. Corresponding to the imaging log response, the GR, ACN, CNLN, GRN, CGRN, RXO, and RT curves of the 5706–5707 m section show anomalous fluctuations, and the porosity curves interpreted by logging are abnormally low, and the mud and siliceous contents are abnormally high in this section. The above phenomena show that the core part of the fault and the suture holes between the breccias are basically filled with mud and siliceous materials, the lithology is dense, the porosity is significantly reduced, and the GR value is significantly high. Compared with the core part of the fault, the rift zones on both sides of the fault obviously have higher porosity and are the layers with good reservoir development.

3.2. Seismic response characteristics

Based on the difference in logging response and porosity between the fault core and the fracture zone on both sides of the Mill Creek 127 well, the following understanding can basically be drawn: in the fracture zone, the fault core is denser and less porous due to the development of the fault mud, while the fracture zones on both sides of the fault core, which have not suffered from the filling of the fault mud, have higher porosity and better physical properties, and they are the location of good reservoir development. In view of the correspondence between the imaging logging results of the fault core of the Mill Creek 127 well and the GR curve (**Figure 3**), this study points out that the width of the fault core of the fracture zone can be identified by the GR logging curve.

Fault nuclei mostly occur in relatively narrow high-strain zones, including faulted mud-tectonic breccia-fractured rocks, ultra-fractured rocks, and local sliding zones. On seismic data, fault cores are usually characterized by disorganized and discontinuous waveforms, weak or locally anomalous strong amplitudes, high-frequency anomalies, waveform discontinuities, bifurcations, or absence of reflections.

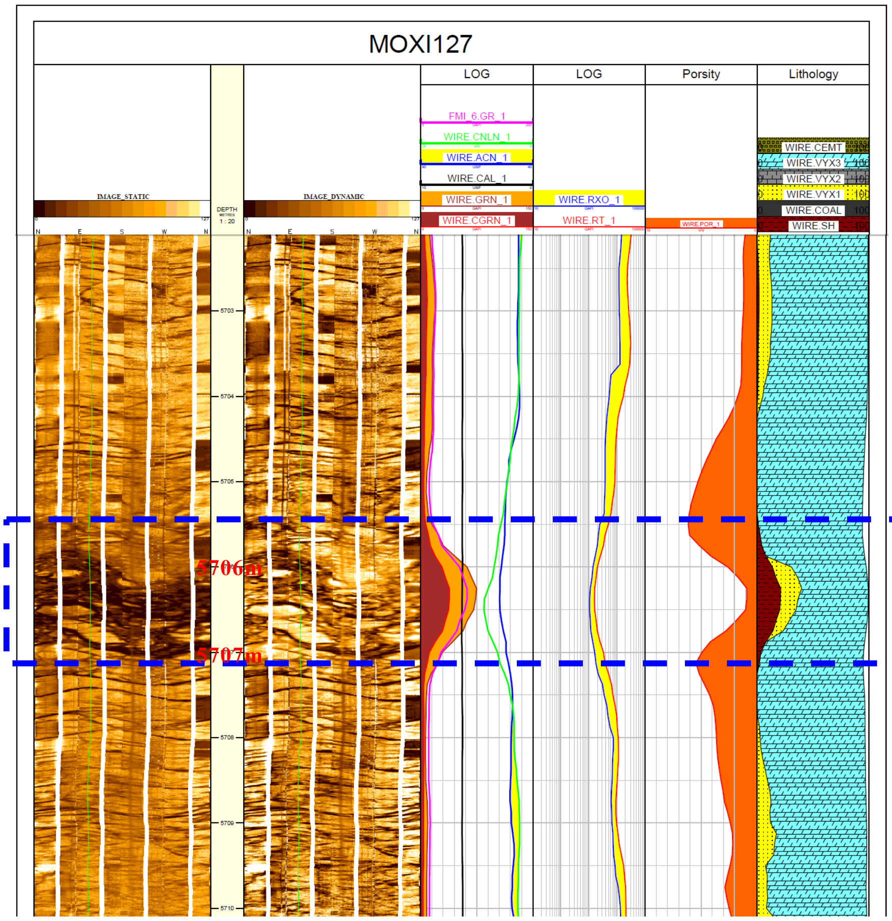


Figure 3. Structure of the fault core zone at Mill Creek well 127 in imaging logging

Table 1. Characteristics of logging response at different locations in the fracture zone

Typology	Deep resistivity	Natural gamma	Density	Neutrons	Sonic	Imaging logging
Nuclear part of fault line	300–500	>30	2.7-2.8	>3	>55	High-gloss stripes
Crushing belt		15-30	2.64–2.7	4–13	>60	Crossed dark stripes of high and low amplitude
Geological fault line	<700	<15	2.4–2.8	1–2	47–49	High-amplitude dark sinusoidal waveform stripe

Fracture zones can be divided into inner and outer zones. The inner zone is adjacent to the fault nucleus and is in contact with the fault nucleus by an abrupt change or a gradual change. The inner zone develops multiple sets of directional cracks, forming an area with dense distribution of cracks, strong local tectonic deformation, forming a breccia, fractured rock development area, stratigraphic discontinuity, and no obvious stratigraphic interface and wave impedance interface within the carbonate rock. The inner zone of the fault fracture zone usually shows weak amplitude on seismic data, unstable wave group, large waveform change, sudden change of same-phase axis, distortion, and bifurcation. The inner zone is usually connected with the fault core, which is difficult to distinguish from the other zone because of its weak and chaotic amplitude.

The outer zone of the fault zone is characterized by the development of cracks, usually dominated by a single group of 1–2 cracks. The degree of crack development is significantly lower than that of the inner zone, the stratigraphic continuity is good, and there is a lack of breccia and fractured rock, which usually shows the characteristics of continuous homogeneous axis, weakened amplitude, and reduced frequency on seismic profiles. The outer zone of the fracture zone has a gradual relationship with the inner zone and surrounding rocks, and it is usually difficult to identify the distribution of the outer zone in conventional seismic profiles, which requires a fine method of fracture and reservoir prediction.

4. Research on the identification method of the broken belt

Fault fracture zones are deformed geological bodies formed around fault cores by the development of fractures and their interactions, and are characterized by the development of fractures, which have different geological structures and petrophysical features from those of the surrounding rocks. As the development of fracture zones usually has geophysical features that are different from those of the surrounding rocks in the seismic data, effective technical means can be preferred through the comparative analysis of different seismic reservoir prediction and characterization methods that portray the characteristics of fault fracture zones from different perspectives.

4.1. Qualitative identification techniques based on fusion technology

For the prediction of fracture-controlled karst reservoirs, firstly, the authors carried out the section and attribute plane interpretation of fractures in the Gaomol area. The authors investigated the section and plane characteristics of fracture development. The study area is located in the relatively stable Chuanzhong Massif, which is less affected by tectonic movement, and folding is not strong. The tectonics is gentle. There are still big difficulties in identifying the strike-slip fractures with the existing data. This area is a low-amplitude tectonic zone, and the folding is weak. The degree of fracture development is not high. And the buried depth of the target layer is mostly 6000 m. The fracture distance is generally small. This area is a low-amplitude tectonic zone with weak folds. The degree of fault development is not high, and the distance between the faults is generally small. Moreover, the depth of the target layer is more than 6000 m. Due to the limitation of seismic resolution, many faults are difficult to identify in conventional seismic data, and there exists a certain degree of multiplicity of interpretations in profile identification and planar combination. In view of this difficulty, targeted research on the interpretation processing method and the preferred extraction of sensitive attributes have been carried out to improve the accuracy of seismic portrayal of fractures, and reliable geological data that can meet the accuracy of fracture identification have been obtained by interpretive processing, on which multi-attribute fusion is used to On the basis of this, multi-attribute fusion is used to identify large-scale first- and second-degree ruptures, and small-scale third- and fourth-degree ruptures are identified by AI interpretation, and the combination of the two methods can improve the reliability of fault interpretation [8].

It is difficult for a single seismic attribute to finely portray the planar spreading characteristics of the rupture. The application of multi-attribute fusion technology can better filter out the invalid information in the curvature, and the information for identifying the rupture features is further strengthened, presenting a clearer linear law in the plane, and being finer in the profile compared with the conventional coherence, which effectively reduces the multiplicity of rupture interpretations. The attribute data body scale fusion function enables the fusion of two seismic attribute data bodies according to the scale relationship. That is to say, the seismic attribute data body (A) and the seismic attribute data body (B) are fused proportionally to generate a new seismic attribute data body (C). **Figure 4** shows a schematic diagram of the proportional fusion method of the seismic attribute data body, and

Figure 5 shows a cross-section of the proportional fusion result of the seismic data body and the coherent data body, from which the fault relationship between the faults and the strata can be clearly seen.

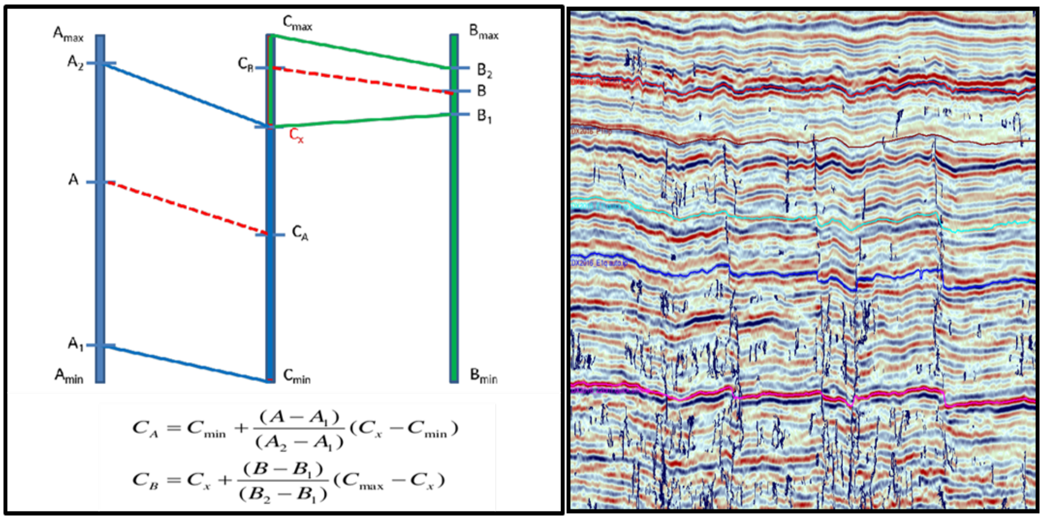


Figure 4. a. Implementation of multi-attribute fusion b. Attribute fusion data body profile

The planar display of the attribute data is fused by the planar display of the attribute data, and according to the parameter test and attribute superiority selection, the three attributes of coherence, maximum positive curvature, and dip attribute, which are more effective, are used for the fusion of multi-attribute to identify the development of the strike-slip segmental rift in the Gaomao-Maolian area of central Sichuan. Comparison of the multi-attribute fusion plan view along the bottom boundary of the Lampshade Formation in the Gaomao-Maolian area with the original coherence plan view shows that there is not much difference with the original coherence in the large fracture inscription, but it is clearer, and the fusion of the maximum positive curvature attribute can lead to a more accurate combination of faults, and at the same time, more secondary fractures can be recognized (**Figure 5**).

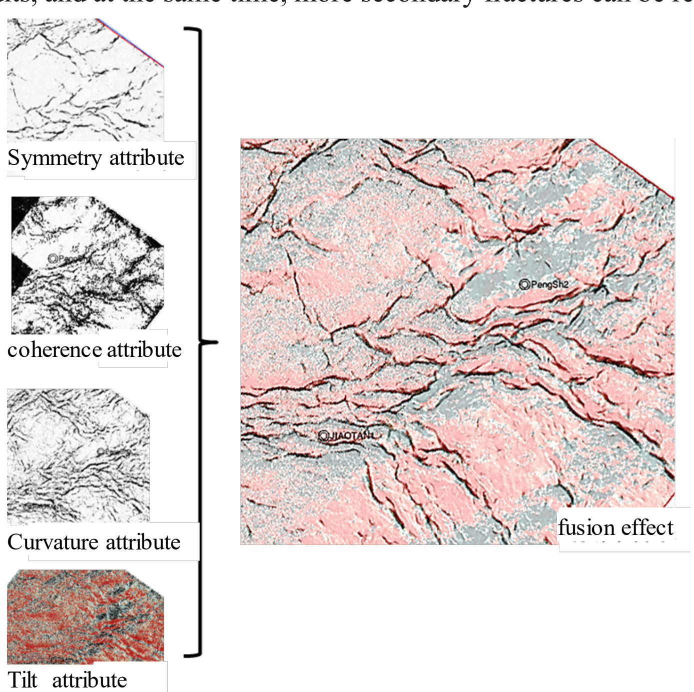


Figure 5. Comparison of multi-attribute fusion effect

The application of multi-attribute fusion technology yields a high-precision fracture interpretation data body, which can clearly reflect the characteristics of the development of high-steep fractures and the fracture zones formed by fracture action in this area, which is crucial for analyzing the fracture-controlled karst reservoirs in the target layer.

4.2. Quantitative identification of fracture zones based on inversion techniques

Applying the abundant real drilling data in the Gaomol area, the authors carry out petrographic interpretation and petrophysical modelling of the reservoir, and obtain the wave impedance body of the target layer through post-stack wave impedance inversion (i.e., sparse impulse inversion), which is the core process of converting the seismic data into longitudinal wave impedance data. Through the feasibility analysis of wave impedance inversion as mentioned above, the authors believe that the seismic data and drilling data of this area can meet the requirements of post-stack wave impedance inversion. Based on the prepared data, post-stack wave impedance inversion generally includes the following key processes: comprehensive seismic and geological calibration, low-frequency model establishment, sub-wave extraction, quality control of inversion results, and analysis of inversion results (**Figure 6**) [9–10].

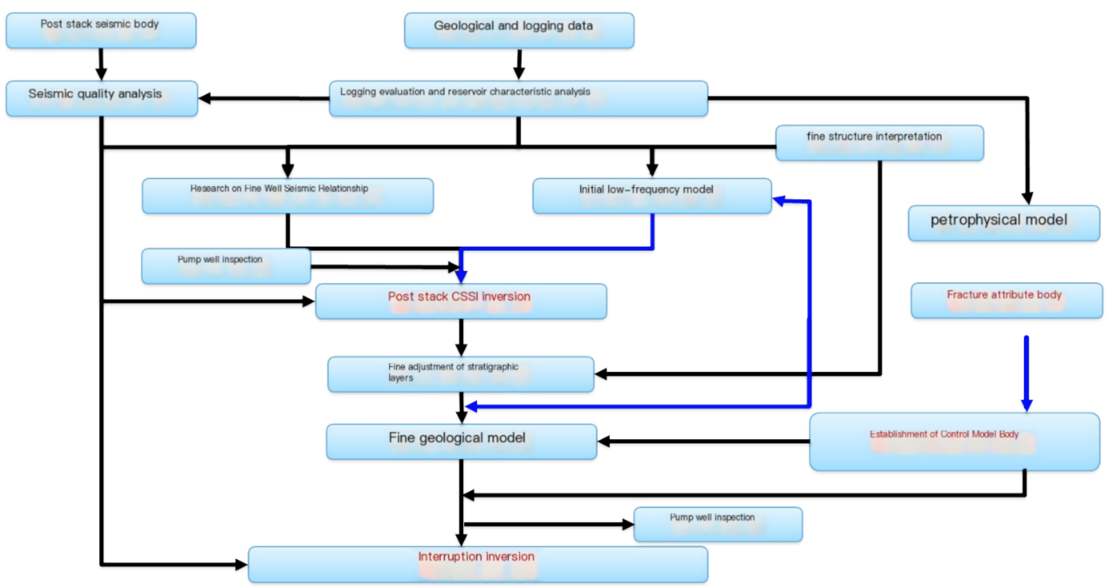


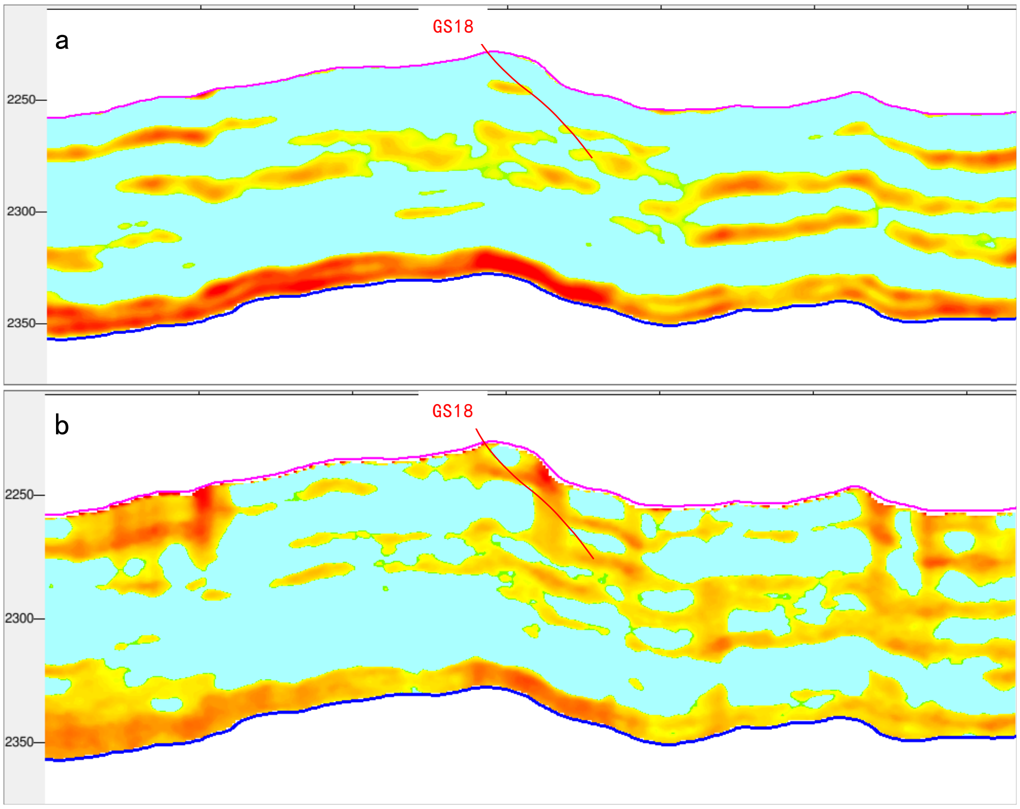
Figure 6. Flowchart of phase-controlled inversion of broken solution

First of all, the authors will look at the initial model establishment. Seismic data usually lacks the low-frequency information in the frequency band below 6–10 Hz. Therefore, the wave impedance model established by the drilling wave impedance data needs to be used in the inversion results to supplement the missing low-frequency information in the post-stack inversion results. The wave impedance model is based on the establishment of a geological model, using different interpolation and extrapolation methods to interpolate the longitudinal wave impedance data at the well point to the whole space. The establishment of a geological model lies in making full use of seismic, logging, and geological data. Starting from seismic data and based on logging data and drilling data, the initial model that basically reflects the geological characteristics of the sedimentary body is established by using the interpreted layers and faults.

Secondly, subwave extraction, subwave is the bridge from reflection coefficient to seismic data, through the fold product of reflection coefficient and subwave, seismic waveform data can be generated. Whereas the inversion process is to use seismic data and subwave to obtain the reflection coefficient data through back calculation, and then use the reflection coefficient to obtain the longitudinal impedance of a process. Therefore, in the process of seismic inversion, the accuracy of the subwave has a very important impact on the reliability of the seismic inversion results. The calibration of subwave extraction and synthetic record is a continuous cycle and gradual process, until the calibration result reaches the best, the subwave extracted from each well with fine calibration is compared, and the phase and amplitude of the subwave are more consistent. Based on this, the average subwave is extracted for the inversion, and an ideal inversion result can be obtained.

Conventional inversion obtained matrix pore reservoir prediction results, further apply the fracture-control model constraints established by the fracture attribute fusion to carry out the secondary inversion, the fracture-control model constraints of the inversion can highlight the non-homogeneous information in the seismic data near the fracture zones, finely delineate the characteristics of the development of fracture-controlled reservoirs, and carry out a fine description of the fracture-controlled reservoir to improve the success rate of the drilling wells.

Fracture-controlled karst inversion can effectively highlight the non-homogeneous information near the fracture zone and finely characterize the reservoir development near the fracture. **Figure 7** shows the comparison of the conventional inversion profile and fracture control inversion profile of GS18 well. The well is located in the fracture zone, and the conventional inversion shows that the internal reservoir at the well point is developed in layers, and the results of fracture control inversion show that the reservoir is developed vertically, and the well is drilled to develop a large set of thick reservoir vertically, and the test production is 240,000 m^3/d, which is consistent with the results of the fracture control inversion, and the results of the fracture control inversion at further confirms that the results of the fracture control inversion are highly reliable.



(a) Conventional inversion impedance profile (b) Control inversion wave impedance profile

Figure 7. Comparison of wave impedance planes between conventional and disconnected inversion

5. Conclusion

The internal structure of the fracture zone is divided into zones, mainly including the fracture zone and the induced fracture zone. The fracture zone is characterized by the development of cohesive and non-cohesive fault rocks, and there are differences in the internal structure of the fracture zone depending on the lithological properties of the fractured strata.

The channels for oil and gas transport along the fractures are changing, and the mechanism, power, duration, transport speed and efficiency of transport along each type of channel are different, which are basically divided into three stages: during the period of fracture activity, oil and gas are transported along the dominant fissures rapidly in the form of pipeline flow under the action of "seismic pumping", and this is the stage of highest efficiency of fracture transport; after the cessation of fracture activity and before the filling of induced fractures, oil and gas are transported along the induced fractures in the form of buoyant flow or pipeline flow, and this is the stage of higher efficiency of fracture transport. After the fracture activity stops and before the induced fracture is filled, oil and gas are transported along the induced fracture in the form of buoyant flow or pipeline flow, which is the stage with higher efficiency of oil and gas transport along the fracture; after the induced fracture is filled, oil and gas are transported along the non-cohesive fault zone in the form of seepage flow, which is the stage with lower efficiency of oil and gas transport along the fracture. The oil and gas transport along these three channels is not simultaneous, but a continuous process.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Zhang MS, Wang BJ, Wang X, et al., 2024, Identification of the Internal Structure and Reservoir Control of Liaozhong No.1 Strike Slip Fault: A Case Study of Jinzhou A Structure. Frontiers of Marine Geology, 40(4): 29–38.

[2] He YF, Chen SY, Liu YY, et al., 2025, Research on Reservoir Modeling of Fracture-Controlled Fracture Cave Type Oil and Gas Reservoirs: Taking Shunbei No. 4 Fault Zone as an Example. Geological Science and Technology Bulletin, 44(3): 108–121.

[3] Tang H, Wu GH, Ma BS, et al., 2025, Characteristics and Significance of Permian Strike Slip Faults in the Central Sichuan Region. Modern Geology, preprint, 1–17.

[4] Wan XG, Wu GH, Xie E, et al., 2016, Seismic Prediction of Carbonate Fault Fracture Zone in Halahatang Area, Tarim Basin. Petroleum and Natural Gas Geology, 37(5): 786–791.

[5] Jiang GP, Fu G, Sun TW, 2017, Using Seismic Data to Determine the Differences in Oil and Gas Transport Capacity and Oil and Gas Enrichment of Oil Source Faults. Advances in Geophysics, 32(1): 160–166.

[6] Zhang SP, Lv BF, Xia B, et al., 2007, The Cenozoic Structural Transformation and its Significance in Controlling Oil in Dongying Depression. Geotectomics and Mineralogy, 2007(3): 281–287.

[7] Di GD, Chen YJ, Chen K, et al., The Distribution and Activity of Strike Slip Faults in the Gaoshiti Area of the Sichuan Basin and their Control and Significance for the Development of Dolomite Reservoirs in the Permian Qixia Formation. Acta Petroleum Sinica, 45(12): 1761–1782.

[8] Zhao ZY, Zhou XJ, 2024, Seismic Characterization Method for Fault Fracture Zones based on Multi-attribute Fusion. Petrochemical Technology, 31(12): 229–231.

[9] Hu TM, 2025, Application Analysis of Comprehensive Geophysical Exploration Methods for Fault Zones. Science and Industry, 25(9): 1–6.

[10] Xu SL, Sun YH, Wang B, et al., 2024, Scale Identification and Application of Fault Fracture Zones under Well Seismic Combination. Petroleum Geology and Engineering, 38(4): 17–23.