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ORIGINAL PAPER

A study on the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles

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Abstract

Marlstone reservoirs are closely related to the degree of fracture development and their hydrocarbon accumulation are also controlled by the distribution of fractures. Hence, the prediction of fracture development zones is very important to the discovery of fractured oil and gas reservoirs. Tectonic movements and their intensities are one of the key factors affecting the formation of fracture systems and the distribution of tectonic stress field has great impact on the generation of fractures. Therefore, taking marginal subsags in the Jiyang Depression, Eastern China, as an example, this paper studied the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles. This study proposed the equivalent geological model and elastic characterization parameters for the fractured marlstone reservoirs in study area, analyzed the seismic response patterns, anisotropy characteristics, and seismic wave-field distribution of the marginal subsags in the Jiyang Depression, discussed the influences of fracture filling fluid, density, inclination, orientation, and layer thickness on the characteristics of seismic wave propagation in fractured marlstone reservoirs, and finally explored the shear wave splitting phenomenon and the exploration and development significance of the seismic wave propagation in fractured marlstone reservoirs. The study results show that the fracture filling fluid can lead to the dispersion and attenuation of seismic wave propagating in the medium, and rock saturated with fluid can exhibit frequency-dependent attenuation and dispersion due to wave-induced fluid flow between pores and fractures. The change of fracture density can make seismic wave appear anisotropic and biphasic and the difference between the high and low frequency of the longitudinal wave phase velocity becomes more and more obvious. The change of fracture inclination and orientation can cause the shear wave splitting phenomenon, in which the fast shear wave polarized parallel to the fracture with a fast velocity and a slow attenuation and the slow shear wave is polarized in the direction perpendicular to the crack with slow velocity and fast attenuation. The change of fracture layer thickness can make because the change of phase velocity and attenuation and the larger the thickness of the fracture layer is, the greater the difference between the reflection amplitude of the bottom interface and that of the non-fracture layer is. The study of characteristics of seismic wave propagation in fractured marlstone reservoirs can effectively obtain the multi-directional shear wave impedance and then fine characterize the fracture strike and density of tight oil fractured reservoir, which has important theoretical research and practical exploration significance. The study results provide a reference for further researches on the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles.

Keywords Fractured marlstone reservoir; · Seismic wave propagation; · Seismic characteristics; · Mechanics principle

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Introduction

As the degree of global oil and gas exploration increases, fractured marlstone hydrocarbon reservoirs have become one of the important new fields of exploration. Years of exploration practice have shown that marlstone reservoirs are more difficult to study than clastic reservoirs (Chen et al. 2016). The reservoir space of marlstone is dominated by secondary pores, which determines that it has stronger reservoir heterogeneity, and it is more likely to be affected by late diagenetic transformation, thus increasing the difficulty of reservoir prediction. Marlstone reservoirs are closely related to the degree of fracture development and their hydrocarbon accumulation are also controlled by the distribution of fractures (Li et al. 2019). Hence, prediction of fracture development zones is very important to the discovery of fractured oil and gas reservoirs. Due to the compaction from overlying load, horizontal or low-angle fractures almost disappear, while vertical and high-angle fractures are easily preserved. The existence of these fractures causes anisotropic characteristics in the process of seismic wave propagation (Loucks et al. 2020). Analyzing the anisotropic characteristics of seismic waves is one of the important contents of using seismic data to detect fractures. Since the formation and distribution of fractures are not only affected by their lithology, diagenesis, etc., tectonic movements and their intensities are also key factors affecting the formation of fracture systems and the distribution of tectonic stress field has great impact on the generation of fractures. Therefore, the study of the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles has important theoretical research and practical exploration significance (Zhao et al. 2020).

The Jiyang Depression, located in the southeast of the Bohai Bay Basin, Eastern China, is one of the typical oil-rich depressions in the Bohai Bay area. This depression is an eastward spreading, westward converging, and nearly east-west striking first-order negative structural unit, which is divided into four main sags and several uplifts: Dongying Sag, Zhanhua Sag, Huimin Sag, Chezhen Sag, Yihezhuang Uplift, Chenjiazhuang Uplift, and Linfanjia Uplift, etc. (Ren et al. 2002). Moreover, a series of NEE and WE-trending sag-controlling faults, such as the Chengnan fault, Wudi fault and Shicun fault are developed in this area. With the increase in the degree of oil and gas exploration, the division of structural unit has become more refined. In recent years, the Sanhecun Subsag, Qingnan Subsag, Fulin Subsag, etc., have been identified on the periphery of these main sags (Tian et al. 1992). The main source rocks in the Jiyang Depression are composed of the salty lake-freshwater lacustrine sedimentary rocks of the Shahejie Formation, which mainly includes the upper part of the fourth member, the lower and middle parts of the third member, and the first part of the first member (Allen et al. 1997). The strata are dominated by laminar calcareous mudstone, marlstone, and lime mudstone with a certain amount of lime shale, argillaceous dolomite and other carbonate rocks. The organic matter type is mainly sapropel type and mixed type, with the characteristics of high abundance of organic matter and wide range of maturity, and its high hydrocarbon generation potential has laid the material foundation for oil accumulation in the Jiyang Depression (Bing et al. 2019).

Taking marginal subsags in the Jiyang Depression, Eastern China as an example, this paper studied the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles. This study proposed the equivalent geological model and elastic characterization parameters for the fractured marlstone reservoirs in study area, analyzed the seismic response patterns, anisotropy characteristics, and seismic wave-field distribution of the marginal subsags in the Jiyang Depression, discussed the influences of fracture filling fluid, density, inclination, orientation, and layer thickness on the characteristics of seismic wave propagation in fractured marlstone reservoirs, and finally explored the shear wave splitting phenomenon and the exploration and development significance of the seismic wave propagation in fractured marlstone reservoirs. The study results provide a reference for further researches on the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles. The detailed chapters are arranged as follows: the “Methods and principles” section proposes the equivalent geological model and elastic characterization parameters for the fractured marlstone reservoirs in study area; the “Characteristics of seismic wave propagation in fractured marlstone reservoirs” section analyzes the seismic response patterns, anisotropy characteristics, and seismic wave-field distribution of the marginal subsags in the Jiyang Depression and discusses the influence of various factors on the characteristics of seismic wave propagation; the “Discussions” section explores he shear wave splitting phenomenon and the exploration and development significance of the seismic wave propagation in fractured marlstone reservoirs; the “Conclusions” section is conclusion.

Methods and principles

Equivalent geological model of fractured marlstone reservoirs

The forward simulation of the rock physics model is realized by the finite difference decomposition of the elastic wave equation. It first needs to establish a petro-physical model of the reservoir, that is, the reservoir is divided into a rock skeleton model and a pore model in the rock according to the equivalent medium theory. To establish a petro-physical model, the velocity of the vertical and horizontal waves of the formation, the density of the rock, the size of the pore space and the fluid elastic parameters in the pores are required (Yin and Ding 2019). The quantitative evaluation of marlstone fractures is carried out on the basis of the qualitative evaluation of fractures. Since the usual quantitative evaluation methods of reservoirs are generally established based on homogeneous media. The heterogeneity of fractured marlstone reservoirs is extremely strong and the quantitative evaluation of fractures is still in a stage of continuous development and improvement. The equivalent geological model of fractured marlstone reservoirs is shown in Fig. 1.

Rocks generally have anisotropic characteristics and the reason for this anisotropy may be the mineral composition and arrangement of the rock, the pore structure and fracture network, or the fluid distribution inside the rock. The stress-strain constitutive relationship Q_{ij} of elastic anisotropic rock can be characterized as:

$$Q_{ij} = \frac{a_{ij} - b_{ij}}{c_{ij} - b_{ij}} \tag{1}$$

where a_{ij} is the stress tensor; b_{ij} is the strain tensor; c_{ij} is the elastic tensor of the rock. For an isotropic solid medium, the relationship between stress and strain can be expressed in the following form with two parameters:

$$W_{ij} = k\left(\frac{1}{d_{ij}} - \frac{1}{e_{ij}}\right)\left(\frac{1}{f_{ij}} - \frac{1}{g_{ij}}\right) \tag{2}$$

where k is the Lame constant; d_{ij} is the body strain; e_{ij} is used to characterize the difference between the vertical and horizontal speed of the primary wave; f_{ij} is the number of constituent components; and g_{ij} is the volume component of the medium.

It is supposed that the correlation coefficient between t time on the longitudinal survey line, the delay between (x_i, y_i) and (x_{i+1}, y_i) and u of the seismic trace is l is c_x; the longitudinal survey line t time, seismic trace The correlation coefficient between (x_i, y_i) and (x_{i+1}, y_i) and the delay between u is l is c_y; then the correlation coefficient of the vertical and horizontal lines is combined to obtain the correlation coefficient E_{xy} as:

$$E_{xy} = \sum_{x,y=1}^{n} h \frac{t(x_{i+1} - x_i)}{c_x} - l \frac{u(y_{i+1} - y_i)}{c_y} \tag{3}$$

where h is the coherence coefficient; l is the inclination function between time and seismic trace. The split shear wave contains physical property information along the ray path, and there is a time delay between the two shear waves.

Qualitative evaluation is guided by geological thinking, combined with multiple disciplines as a means, making full use of various information displayed by logging data and various dynamic and static data of a single well, combined with comprehensive research on the geological characteristics of oil and gas reservoirs, and finally predicting fractures. After the formation is deformed and bent in a certain direction, the part above the neutral surface is subjected to tensile stress, and the rock can form tensile fractures. The degree of fracture development is proportional to the curvature value, so the curvature of the formation can be used to reflect the relative development of fractures.

Elastic characterization parameters of fractured marlstone reservoirs

Forward modeling is an effective method to study the pattern of seismic wave propagation in complex media. The three-dimensional viscoelastic anisotropic medium requires multiple relaxation functions to control its attenuation characteristics. The shear wave splitting phenomenon can be clearly seen in the wave-field snapshot, in which fast shear waves are polarized along the direction parallel to the fracture, and the speed is fast, and the attenuation is slow; the slow shear wave is polarized along the direction perpendicular to the fracture, and the speed is slow, and the attenuation is faster (Thebti et al. 2018). According to the polarization characteristics of shear waves, the polarization direction of fast shear waves can be measured to represent the direction of fracture development; and the time difference of arrival of fast and slow shear waves in seismic records is related to the density of fracture development and the angle at which shear waves enter the fracture.

Assuming that the medium contains a set of parallel fractures connected with equal-diameter pores, and the fluid

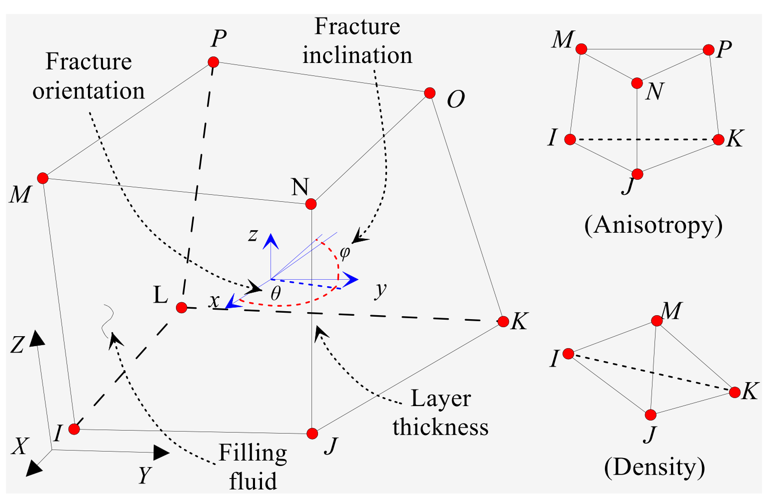

Fig. 1 Equivalent geological model of fractured marlstone reservoirs

pressure between the fractures and the surrounding pores is locally balanced. A set of anisotropic parameters is introduced into the model and the parameters that determine the sensitivity of the fractures to fluid are also proposed, so the parameter Y that determines the sensitivity of the fracture to the fluid is proposed as:

$$Y=\sqrt{\left(\frac{u}{I}-\frac{z}{U}\right)\left(\frac{w}{O}-\frac{z}{P}\right)} \tag{4}$$

where u is the fluid influence factor at low frequencies; v is the bulk modulus of the fluid in the fracture; w is the bulk modulus of the solid framework particles; z is the bulk modulus of the isotropic dry fractured rock; I is the total rock porosity; U is the Poisson's ratio of the isotropic dry fracture medium; O is the fracture density; P is the porosity of the fracture.

Another situation is that in the case of medium and high frequencies, the fluid does not have enough time to reach a local equilibrium state. At this time, the fluid influence factor A_{ij} is:

$$A_{ij}=\frac{\alpha S_{ij}-\beta D_{ij}}{\gamma} \tag{5}$$

where α is the elastic modulus of the rock background medium; β is the Lame constant of the background rock; S_{ij} is fracture density; D_{ij} is fracture radius; γ is the discontinuous displacement of the fracture surface.

The permeability direction value of anisotropic porous media has the form of symmetrical tension, which can be expressed as in a two-dimensional plane:

$$F_{ij}=\frac{G_{ij}}{g_x}\cdot\frac{H_{ij}}{g_y} \tag{6}$$

where g_x and g_y are the horizontal permeability with the long and short main axes perpendicular to each other; G_{ij} is the multiple relationship value; H_{ij} is the permeability in other directions.

Therefore, theoretically, the relevant information of shear wave splitting can be used to predict the azimuth and density parameters of formation fracture development. For the prediction of the underground fracture zone, because the magnitude and direction of the boundary force often have unknown characteristics, it needs to be combined with structural geological analysis, and a series of assumptions are used to repeatedly debug to quantify it. The process of determining the boundary conditions is the re-understanding of the process of petroleum geological tectonic movement. Through comprehensive analysis of seismic interpretation data, drilling data, geological reports, and rock physical testing in the area, the boundary conditions of the mechanical model that are consistent with geological phenomena and structural patterns in the study area are determined.

Characteristics of seismic wave propagation in fractured marlstone reservoirs

Response characteristics of marlstone

For fractured marlstone reservoirs, the resistivity value of tight marlstone can be as high as tens of thousands or higher; the deep and shallow lateral amplitudes of fractures in fractured reservoirs are significantly reduced, often showing obvious spike-like low values. The characteristics of the double lateral curve are locally zigzag type; the porosity curve of the micro-fractured reservoir is close to the framework value, and the double lateral direction is high resistance and zigzag; the fracture-cavity type reservoir is affected by fractures and crystal caves (Inozemtsev et al. 2019). The degree of development has a great influence, the bilateral lateral resistivity is generally high, and the acoustic, neutron, and density logging curves are concave and convex.

The time difference between the fast component shear wave and the slow component shear wave is proportional to the density of rock fissures in the direction of the ray path, and is also related to the incident angle of the rays passing through the ordered micro-fractures. Therefore, the horizontal component of the shear wave is the polarization direction is combined into:

$$R_i=m\cdot p_i e^{x_i}-o\cdot q_i e^{y_i} \tag{7}$$

where R_i is the polarization coefficient; m is the time; o is the inclination; p_i is the seismic data; q_i is the transposed matrix.

The theoretical basis of the model is that both the model medium and the solid medium should follow the wave equation T_{ij} on which seismic wave propagation is based. According to the unity of the wave equation, the following formula can be derived by considering basic parameters such as speed, time, and length:

$$T_{ij}=\frac{r_{ij}-s_{ij}}{t_{ij}} \tag{8}$$

where r_{ij}, s_{ij} and t_{ij} are the propagation speed, travel time and distance of the wave in the actual formation medium, and the negative sign is the wave parameter in the model medium.

The sign of the principal stress component adopts the provisions of rock mechanics in this study: the positive value is the compressive stress and the negative value is the tensile stress. In the favorable zone of the fracture, the tensile zone with the negative value of the principal stress should be found, because for a specific rock mass, tensile stress is more prone to fractures. For shear stress, a relatively high value area should be selected, because the high value area of shear stress is generally related to the favorable development zone of fractures (Fig. 2). According to the polarization characteristics of shear waves, the polarization direction of fast shear waves can be measured to represent the direction of fracture development; and the time difference of arrival of fast and slow shear waves in seismic records is related to the density of fracture development and the angle at which the shear waves enter the fracture. Therefore, in theory, the relevant information of shear wave splitting can be used to predict the azimuth and density parameters of formation fracture development.

For intra-layer fractures, on the noise-free and noise profile, the two fracture development areas appear to be obviously irrelevant, but the angle of the fracture cannot be determined, and the irrelevant area is related to the scale of the fracture. For the interlayer fractures, on the coherent section with no noise and noise, the two fracture development zones also show obvious incoherence, but the fracture development zone on the right reflects more clearly, which may be related to the fracture development zone (Kharazova et al. 2016). The local mudstone interlayer is also reflected in the coherent section, and its characteristics are similar to the interlayer fracture, but it can be distinguished by the incoherence of the coherent axis of the conventional section. Judging from its seismic model, the two fracture development zones on the noise-free seismic profile are reflected, both of which are cluttered reflections, and deform the normal stratum interface reflection, but the larger fracture zone on the right is more deformed. Obviously, on the noise seismic profile, the fracture development area on the left becomes blurred, and the fracture development area on the right can still be identified, showing local messy reflection characteristics. On the noise-free seismic profile, both fracture development zones reflect chaotic reflections, but the low-angle fracture development area on the right is more obvious; on the noise seismic profile, the high-angle fracture development area becomes blurred, and low-angle fracture development areas can still be identified, but they are all local and messy reflection features.

Anisotropy analysis

Fractures of different grades and sizes from micro-fractures to faults are widely developed in the underground medium, which strongly affects the seismic wave propagation and produces scattering and fracture-induced anisotropy. When the size of the fracture is much smaller than the seismic wavelength, the seismic wave propagation in the fracture medium can be described as the anisotropy induced by the fracture. Fractured porous media usually contain two types of pores, namely matrix pores and fracture pores. The matrix system and the fracture system have their own different porosity and permeability (Tyapkin et al. 2020). Therefore, for this kind of media, it is different from a single porous medium, except that the matrix is considered. In addition to the porosity and permeability, the porosity and permeability must be considered at the same time.

The seismic wave attenuation data is expressed in the form of quality factors just like the attenuation coefficient. If the attenuation coefficient is a linear function of frequency, the quality factor has nothing to do with frequency. The measured amplitude K of the rock sample attenuation coefficient of a specific angular frequency used to correct the transmission loss is:

$$K = \frac{a_r - b_r - c_r}{e_t - f_t - g_t} \tag{9}$$

where a_r is the density of the rock; b_r is the density of the filling fluid; c_r is the velocity of the rock; e_t is the velocity of the filling fluid; f_t is the attenuation coefficient; g_t is the reflection coefficient.

Using cubes of equal area to completely cover the pore structure and counting the number of cubes, the fractal box dimension L can be expressed as:

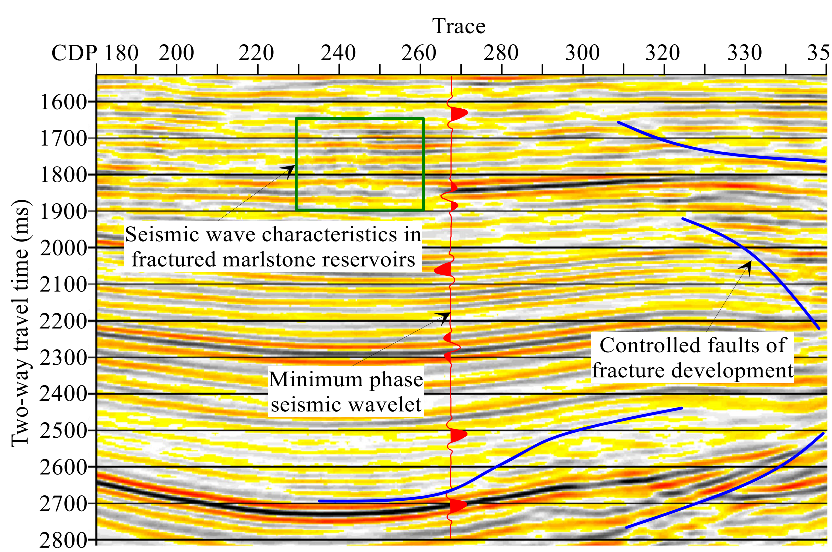

Fig. 2 Response characteristics of fractured marlstone reservoirs in the Shahejie Formation

$$L = \frac{1}{h_v} - \frac{1}{t_v} \quad (10)$$

where h_v is the side length of the cube; t_v is the number of holes and fractures covered by the cube. The size of L reflects the complexity of the pore structure.

The prediction results obtained by the aforementioned reservoir layer-based seismic fracture prediction methods are not the same. The seismic coherence, curvature, and inclination are relatively good, while the primary wave azimuth anisotropy prediction object is relatively macro, and the prediction results are also different from the former, which is difficult to comprehensively predict reservoir fractures. The applicability and pertinence of different seismic fracture detections are the key issues that must be discussed in fracture prediction. It is also the main basis for fracture model establishment and classification prediction and evaluation. The formed supporting methods, technologies and ideas have certain reference value for solving the exploration and development problems of fractured marlstone reservoirs (Wasantha et al. 2017).

The change of background porosity will also affect the elastic properties of the medium. With the increase of porosity, the phase velocity of the equivalent medium decreases significantly in the low frequency range, while in the high frequency range, it does not change significantly. At the same time, the porosity decreases, and the increase will also increase the anisotropy of the medium, and different shale content in marlstone determines the degree of fracture development. When there is gas in the pores, the frequency dispersion and attenuation are the least obvious, and the speed dispersion and attenuation are only found in a very high frequency range; when there is oil, the medium has the most serious dispersion and attenuation, and the salt water comes next. Finally, the influence of the fracture density on the phase velocity and anisotropy parameters of the equivalent medium is analyzed, and it is found that the increase of the fracture density increases the dispersion and attenuation of the medium speed, the difference between the high and low frequency limits is large, and the increase of the medium to the opposite side (Zare et al. 2020). Marlstones with higher shale content are not easy to form fractures, while pure marlstones are easy to form effective fractures under stress. Obvious fractures and pores are displayed on the conventional seismic curve, but for micro-fractures and dissolved pore type reservoirs, the evaluation accuracy of conventional seismic data is low, and the imaging seismic processing results are used in the evaluation of dissolved pore type and fracture type reservoirs in this well to the unique role.

Seismic wave-field characteristics

Due to the compaction of the overlying load, horizontal or low-angle fractures almost disappear, while vertical fractures and high-angle fractures are easily preserved. The existence of these fractures causes anisotropic characteristics in the process of seismic wave propagation. Analyzing the anisotropic characteristics of seismic waves is one of the important contents of using seismic data to detect fractures. According to the theory of seismic scattering, the attenuation of seismic waves is related to the spatial variation of fracture density. The attenuation is slow when propagating along the fracture strike direction, while the attenuation is fast in the direction perpendicular to the fracture strike direction. Vertical fractures, high-angle oblique fractures and mesh structure fractures can cause seismic energy attenuation and uneven distribution of seismic energy. Theoretical studies have shown that, compared with tight rock formations, when the reservoir contains fluid such as water, oil or gas, it will cause the scattering of seismic waves and the attenuation of seismic energy. Therefore, analyzing the attenuation change characteristics of earthquakes, it can be seen that the greater the attenuation gradient in the reservoir, the better the physical properties of the reservoir (Xu et al. 2020). Tectonic stress is an important factor affecting the development of fractures, and tectonic activity is the direct cause of fractures. In the process of tectonic evolution, structural deformation causes stress redistribution within the formation, and various different fracture systems appear accordingly, which provides storage space for the formation of fractured oil and gas reservoirs. The probabilistic distribution of fracture density in seismic wave-field and inverted results of primary and shear waves in the Shahejie Formation is shown in Fig. 3.

Since the travel time difference between the fast and slow shear waves from the top and bottom interfaces of a thin reservoir cannot be determined with the accuracy of identifying the lateral changes of anisotropy. The velocity-end curve in natural coordinates based on the reflection components in the fast and slow directions contains two sensitive and easy-to-determine characteristics. For typical seismic frequency bands, the outer edge of this velocity-end curve is close to a long and narrow ellipse, the orientation of its long axis can determine the polarization angle, and the length ratio of its short axis to the long axis determines the aspect ratio. The interference wave caused by heterogeneity will erase the fine split share wave or lead to false detection of share wave splitting. Therefore, reliable split shear wave detection and analysis techniques must consider the possible interference of other waves. In addition, all three components should be used in the inclined stratigraphic area and the three-dimensional structure area. Using shear wave seismic to extract the fracture parameters, in the current methods and technologies, the seismic wave parameters related to the fracture properties are basically extracted quantitatively, and in the process of converting to the fracture parameters, it is mostly a qualitative method. In other words, quantitative parameters are only used to qualitatively reflect the nature of fractures.

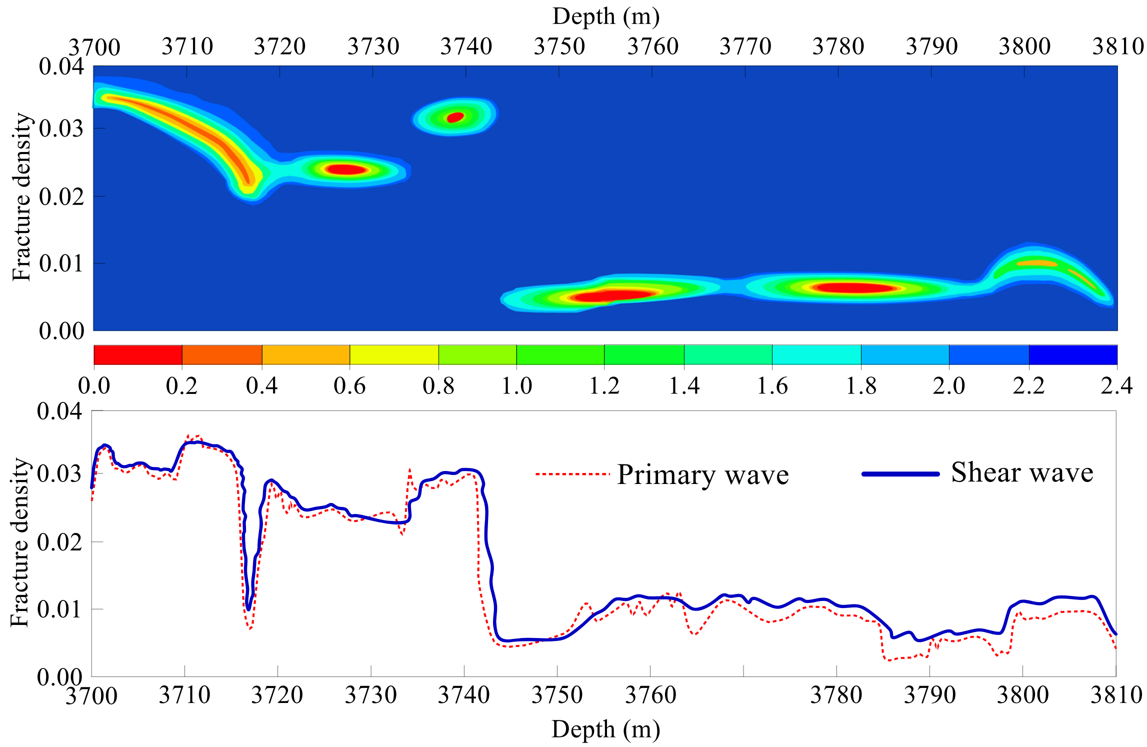

Fig. 3 Probabilistic distribution of fracture density in seismic wave-field and inverted results of primary and shear waves in the Shahejie Formation

Seismic response patterns

The analysis of actual data shows that in the marlstone fractures developed in the study area, the parameters of time difference of primary wave, time difference of shear wave and Poisson's ratio all show high values, while the Lame constant, bulk modulus and shear modulus are all high. The seismic wave group is characterized by weak reflections, increased reflection events and rapid lateral changes, and has obvious characteristics of fracture anisotropy. The analysis of actual data shows that in the marlstone fractures developed in the study area, the parameters of primary wave time difference, shear wave time difference and Poisson's ratio all show high values, while the Lame constant, bulk modulus and shear modulus are all high. The seismic wave group is characterized by weak reflections, increased reflection events and rapid lateral changes, and has obvious characteristics of fracture anisotropy (Gao and Duan 2017). The fracture tectonic stress field analysis method is based on the theory of tectonic mechanics, using the geometric information and lithology information of the formation to estimate the stress field of the formation, including the curvature tensor, deformation tensor and stress field tensor of the formation, so as to obtain. Figure 4 shows the analytical framework of seismic response patterns in fractured marlstone reservoirs based on mechanical principles. The distribution results of principal curvature, principal strain, and principal stress are used to predict favorable locations for fracture development. However, the overall distribution regularity of the attributes of different azimuths is poor, and it is difficult to be well connected with geological features such as structure and fault distribution.

As the temperature and pressure conditions change, the various attribute parameters of seismic waves also show regular changes. The characteristics of the changes in these parameters are basically similar, but the magnitude of the changes is obviously different. Through the testing of models with different hole densities under temperature and pressure conditions, the influence of different hole densities on the characteristics of seismic waves. As the density of holes increases, the characteristic response of seismic waves under different temperature and pressure conditions is strong or weak. The change of the pore density has a significant impact on the seismic wave properties. With the increase of the pore density, the primary wave velocity, amplitude, main frequency, main amplitude and quality factor basically show a decreasing trend under various temperature and pressure conditions; but the changes of different parameters are obviously different, and the amplitude and quality factor changes are 1–3 orders of magnitude larger than the speed and main frequency. The temperature and pressure conditions also have a significant impact on the seismic wave attribute parameters of the cavity model. With the increase of confining pressure and the decrease of temperature, the primary wave velocity, amplitude, main frequency, main amplitude and quality factor show a gradually increasing change pattern. The changes in the characteristics of the porous reservoir have obvious effects on the

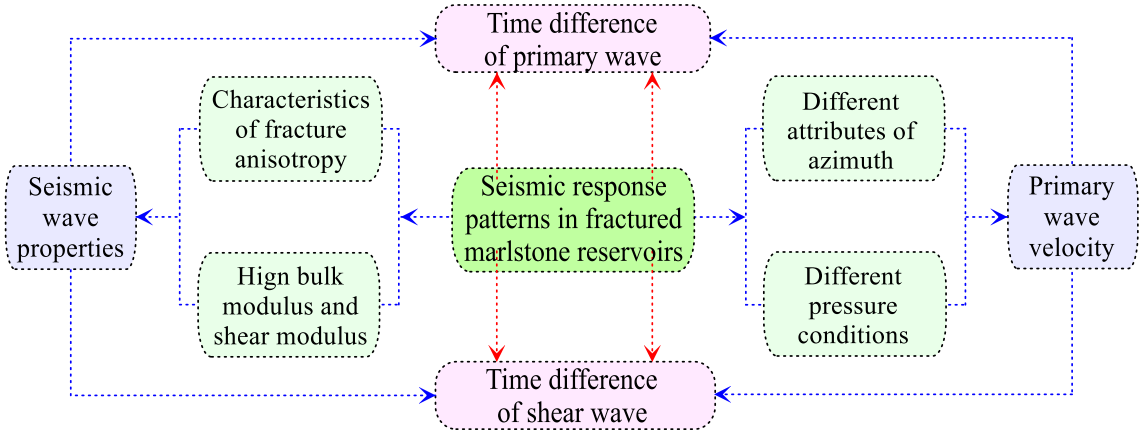

Fig. 4 Analytical framework of seismic response patterns in fractured marlstone reservoirs based on mechanical principles

kinematics and dynamics characteristic parameters of the seismic wave, but the degree of influence is not the same. The dynamic characteristics of seismic waves are more sensitive to changes in the characteristics of porous reservoirs than the kinematic characteristics (Bakhshi and Torab 2016).

Analysis of factors affecting seismic wave characteristics

Filling fluid

The phase velocity appears in a release interval with frequency. The greater the fracture density, the more obvious the difference between the high and low frequency limits; the greater the porosity, the greater the velocity difference, indicating that the greater the porosity, the more fluid can pass through the fracture. Therefore, the difference of the primary wave phase velocity at low frequencies increases with the increase of porosity between pores and the primary wave phase velocity remains unchanged at high frequencies, but in the absence of pores, no fluid flows between pores and fractures. It is also pointed out that as the pores increase, fluid properties become more and more important in saturated rocks. When there is a certain angle between the fracture surface and the ground, especially when the fracture inclination is large, the existence of the fracture will cause the reflection coefficient to change with the offset and azimuth angle, and the change characteristics of the reflection coefficient and the distribution of the fracture (Kong et al. 2017). Combined with specific geological conditions, the degree of fracture development in different regions can also be determined according to the magnitude of the amplitude change. In actual geological conditions, the degree of stratum anisotropy caused by the existence of fractures or other factors is a certain value, which will have an impact that cannot be ignored on the processing and interpretation of seismic data, and it can also be anisotropy.

Fracture density

The matrix pores of marlstone reservoirs are not developed; dissolved pores and fractures are the main types of storage space, among which fractures are the main oil and gas migration channels. Therefore, the scale of this type of reservoir is mainly controlled by the scale of fracture development. However, the reservoir space is dominated by micro-fractures, and the spatial connectivity is poor, which easily leads to high production at the initial stage of the oil test and rapid decline in production afterwards; in addition, the oil layer is also prone to contamination during drilling due to the underdeveloped large fractures. The linear sliding theory regards the flexibility change caused by the fracture as an additional flexibility based on the flexibility of the solid background rock. The entire media flexibility coefficient matrix can be regarded as the sum of the flexibility coefficient matrix generated by the background medium and the fracture (Fig. 5). This theory can better describe the pattern of seismic wave propagation in fractured media, and has become the theoretical basis for studying macroscopic fractured media. In the process of seismic wave propagation, seismic waves received far away from the seismic source have relatively weak high-frequency components and relatively rich low-frequency components. For the reflected wave waveform, it can be seen that when there are elastic fractures in the lower layer, the reflected wave amplitude is stronger than that of elastic isotropy; when the underlying medium is viscoelastic anisotropy, the seismic wave field has anisotropic propagation characteristics. In the case of anisotropy, the wave-front energy is attenuated, showing a small amplitude value.

Fracture orientation

From the perspective of fracture types, whether it is horizontal or oblique fractures, they are all micro fractures. Large fractures are not very developed, but interlayer fractures and high-angle fractures cut each other to form a network of fractures,

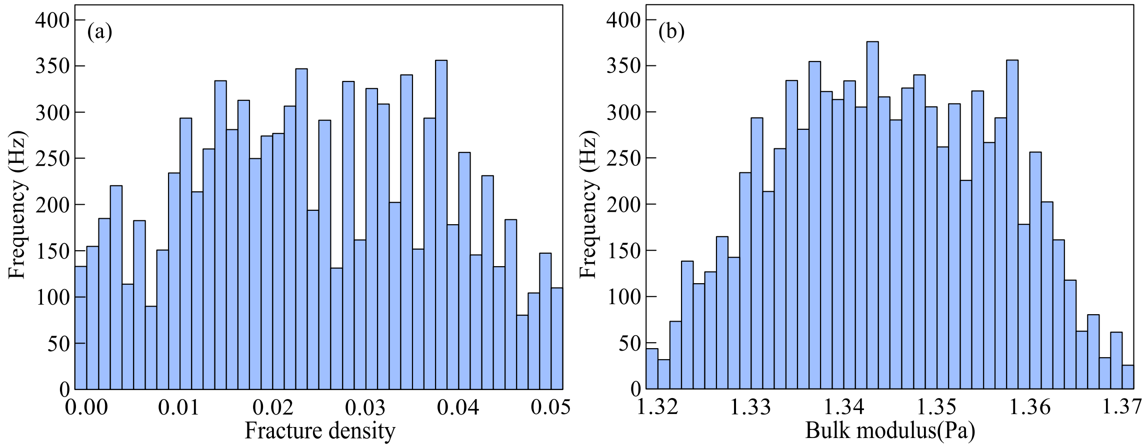

Fig. 5 Seismic wave-field characteristics of fracture density (a) and bulk modulus of filling fluid (b)

which greatly improves the storage properties. The pores of the marlstone itself are not developed, and the fracture is its main storage space and tectonic stress is an important factor affecting the development of fractures. The analysis suggests that the direction of regional tectonic stress is north-east. Under the action of this stress, the rock slides form interlayer fractures and form high-angle tensile fractures, thereby improving the reservoir performance (Deng et al. 2019). Core fractures actually reflect the characteristics of macroscopic fractures on the core and the main factor for the fracture is the regional tectonic stress. Micro-fractures are often not counted due to the limitations of visual observation and resolution capabilities and the effective porosity is the porosity data obtained by the seismic interpretation method. It actually includes the development of macro-fractures, micro-fractures and pores, so it has a higher accuracy than the analysis of core macro-fractures. In general, large fractures are underdeveloped, and the reservoir space is dominated by micro-fractures, with poor spatial connectivity, which easily leads to high fluid production at the initial stage of the oil test and a rapid decline in production afterwards; it is also easy to produce oil layers during drilling.

Fracture orientation inclination

When the fracture azimuth angle is 0°, the model plane is actually a two-dimensional uniform isotropic medium, and the front of the primary wave and shear wave are circular, indicating that in the isotropic medium, the elastic wave velocity has nothing to do with the propagation direction. As the azimuth angle of the fracture increases, the wave front of the primary wave gradually becomes an ellipse in the vertical direction, indicating that the vertical wave speed of the primary wave is greater than the share wave speed, and the shear wave splitting can be seen at this time, and the shear wave splits. As the fracture azimuth angle continues to increase, the anisotropy characteristics become more obvious. When the fracture azimuth angle increases to 90°, the front of the primary wave turns into a diamond shape, and the shear wave appears three-branch phenomenon. The phenomenon of seismic wave absorption and attenuation is caused by the inherent elasticity of the rock matrix, the relative movement of the fluid in the pores and the relative movement of the contact surface, and it is closely related to lithology, porosity and pore fluid saturation (Fig. 6). Theories prove that the effective absorption coefficient is inversely proportional to the cube of the wave velocity. When the rock formation wave velocity changes slightly, the absorption attenuation information is more obvious than the wave velocity change, and its sensitivity far exceeds the sensitivity of the amplitude, frequency, and velocity to the relative lateral changes. In the same lithology, the effective absorption coefficient of oil-saturated oil and gas will increase several times compared with the effective absorption coefficient of water-bearing.

Fracture layer thickness

The comparison results show that the greater the thickness of the fracture layer, the greater the difference between the reflection amplitude of the bottom interface and the non-fracture, that is, the reflection amplitude of the bottom interface becomes smaller when passing through the fracture layer; that is, the thickness of the rock layer is different, which affects the travel time of the formation and the fracture. The thickness of the bottom layer can be inferred from the difference in time difference. When the offset is large, the near-vertical fracture has the greatest impact on the amplitude; when the shot point is closer to the fracture, the impact of the inclined fracture is greater. When the seismic wave propagates parallel to the fracture, its attenuation is smaller, and when the seismic wave propagates perpendicular to the fracture plane, its attenuation is larger. The existence of fractures causes changes in various seismic attributes, and measuring the changes in these seismic attributes can detect fractures (Ali et al. 2016). Among the

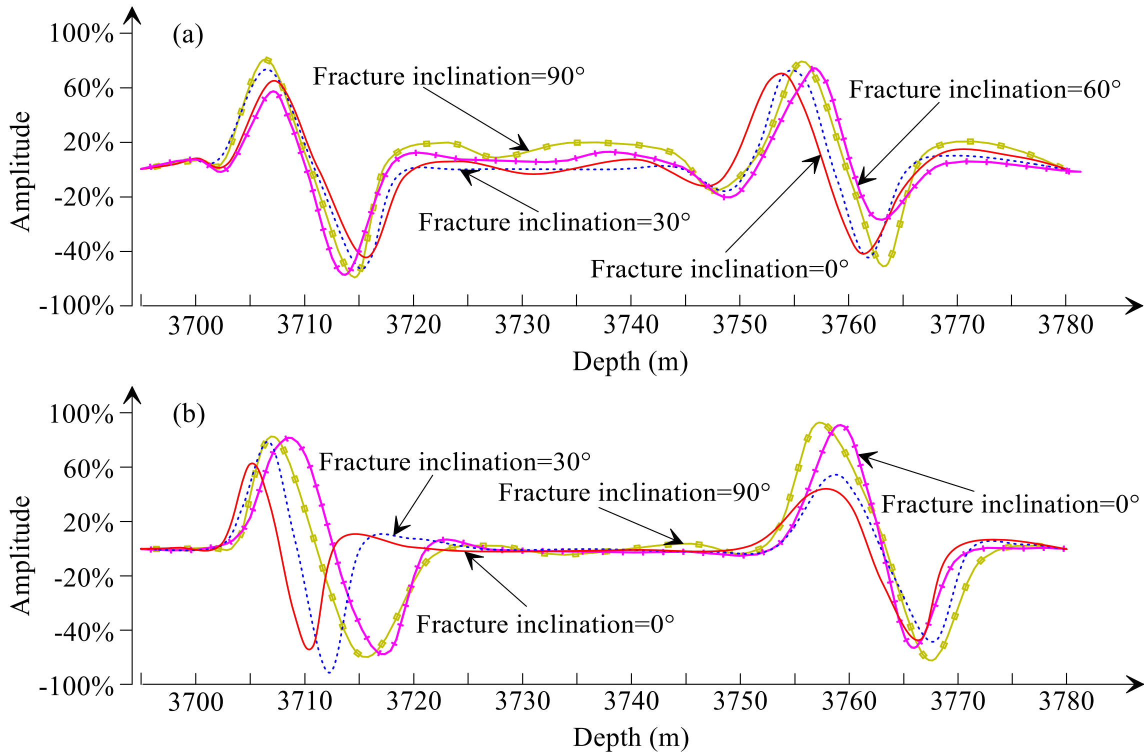

Fig. 6 Amplitudes of primary wave (a) and shear wave (b) with different fracture inclinations

seismic attributes that are more sensitive to fractures are amplitude, layer velocity, time difference, azimuth layer frequency, layer frequency difference, superimposed amplitude, and superimposed amplitude azimuth difference. The formation of underground fissures is closely related to the fracture system. In particular, the formation of high-angle structural fractures is often associated with the fracture system, and the orientation of the fracture is often in good agreement with the direction of the main fault. Therefore, research and development of fracture system identification based on the relevant data volume software, it can identify reliable and detailed fault systems from seismic data, which has important guiding significance for searching for fractured oil and gas reservoirs.

Discussions

Shear wave splitting phenomenon

Since the amplitude is easily affected by noise, acquisition and processing, and the speed obtained before the stack is limited by the speed analysis method itself, the speed obtained from the horizontal or vertical direction, the amount of data is far from meeting the requirements. Amplitude information contains a wealth of medium and high frequency information, and covers a wide range; while the pre-stack velocity analysis results include low frequency content, the organic combination of the two results in new formation impedance and velocity information, which should have the same reflection and anisotropy sensitivity. Wave impedance is the product of velocity and density. For fractured anisotropic formations, it should have the characteristics of azimuth change similar to velocity. The analysis of the conditions required for the formation of rock fractures shows that the strength of the formation rock and the distribution of the in-situ stress directly determine the difficulty of the formation of fractures (Fig. 7). Under the same conditions of in-situ stress distribution, the higher the strength of the formation rock, the less favorable it is for the development and extension of fractures; when the strength of the formation rock is constant, the higher the in-situ stress and the greater the stress difference, the more favorable it is for the fractures. The generation of fractures reduces the bonding force of the rock, so the existence of fractures will lead to changes in the strength of the formation rock and show anomalies in the formation rock strength profile (Mallick et al. 2017).

Low-angle fractures have a more obvious reflection on the seismic profile than high-angle fractures. In-layer seams and trans-layer seams are mostly manifested as messy reflections on the seismic profile, but they do not change the normal reflection characteristics from the interface, but the trans-layer seams make the normal interface reflection deformation larger. The marlstone is mainly manifested as a slight bend of the event axis on the seismic profile and acoustic waves produce abnormal changes in amplitude such as cycle jumps or large and small fluctuations. The resolution of the tuning

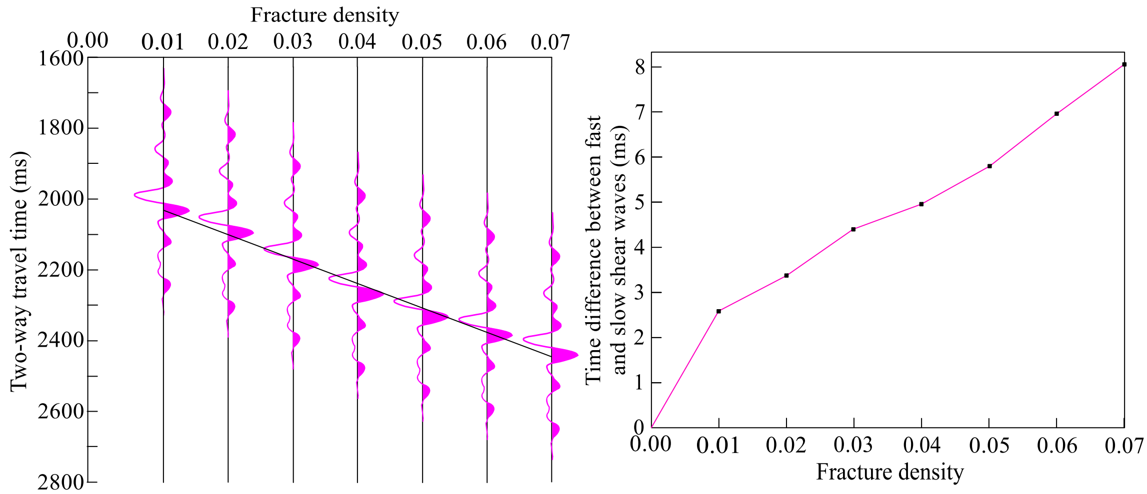

Fig. 7 Trace set of shear wave splitting with different fracture densities

profile of the main frequency after the spectral decomposition process is improved, and the physical properties of the underground rock layer appear more clearly. Therefore, combined with the results of the forward modeling of the model, it is inferred that the black bands with poor coherence may be the response characteristics of fractures or small fractures. Interlayer fractures and interlayer fractures appear to be obviously irrelevant on the seismic profile. The size of the fracture development zone determines whether they can be identified on the seismic profile; local mudstone inter-layers are also reflected on the coherent section, and their characteristics are similar to those on the seismic profile. The fractures are similar, but they can be distinguished by the incoherence between the bending of the event axis on the conventional section and the fractures. The depth of the porosity is relatively high, the compensation density logging has sharp low values, and the depth and shallow bilateral lateral resistivity appear to be high values and positive differences. It can be concluded that these irrelevant features are the basis for verifying the real existence of fractures, so the conclusion is correct.

When there is no fluid in the pores and fractures, the model is equivalent to a transversely isotropic medium; when the fractures and pores are filled with fluid, wave-induced flow will cause dispersion and attenuation of the wave when it is conducted in the medium. Since the dry rock in this model is an elastic body, the fluid-saturated rock will exhibit frequency-dependent attenuation and velocity dispersion due to wave-induced fluid flow between pores and fractures. With the increase of fracture density, the difference between the high and low frequency of the primary wave phase velocity becomes more and more obvious, the change is strong at low frequency, but the phase velocity of the medium at high frequency has little difference. The frequency of the attenuation peak of the inverse quality parameter shifts to the low frequency direction with the increase of the fracture density (Magnusdottir and Horne 2015). The pre-stack method mainly uses the anisotropy of the underground medium, but it is greatly affected by the signal-to-noise ratio of the seismic data. It requires the high accuracy of the seismic data itself, and it also makes the inversion calculation huge and time-consuming. The traditional coherence cube algorithm is based on the principle of starting from one point, using related algorithms to obtain the coherence attribute of the point, and then following the time sequence to calculate the coherence value of each point, and then get the coherent cube slice, and finally repeating this process for the entire coherent body.

Exploration and development significance

The main controlling factors for the development of marlstone fractures are structure, sedimentary environment, diagenesis, of which tectonic is the most important external influencing factor, and sedimentary environment have an impact on the development of various fractures. Diagenesis is the formation of diagenetic shrinkage fractures on the one hand under the control of sedimentary environment; on the other hand, it also reforms other fractures that have been formed. Dissolution, hydrocarbon generation and clay mineral transformation are conducive to the formation and expansion of fractures, while compaction, cementation and re-crystallization are not conducive to the formation of fractures, and can also close or fill existing fractures. General fractures and caves can be effectively identified with the help of conventional seismic data, but in marlstone formations, the conventional seismic wave propagation response characteristics of thin mudstone bands, fractures and bedding fractures are basically the same, and it is also difficult to distinguish horizontally on the seismic profile (Fig. 8). Fractures are separated from mudstone bands and bedding. Effective identification of mud streaks, fractures and bedding is a difficult point in seismic interpretation of marlstone formations. For marlstone formations, due to the lack of matrix pores, dissolved pores and fractures are the main storage spaces for oil and gas, among which fractures are the main migration channels, and the reservoir scale is mainly controlled by the scale of fracture development (Kuchuk et al. 2015).

The marlstone formation has strong plasticity, and it is not easy to develop fractures under normal circumstances, but the effect of tectonic stress can produce a large number of microfractures. In the position of strong formation deformation, the accumulation space and effective migration channel can be formed. Using sub-azimuth pre-stack inversion and shear wave splitting theory methods, multi-azimuth shear wave impedance can be obtained, and then the fracture trend and density of tight oil fractured reservoirs can be finely described. Theory and practice have proved that the fracture direction and density obtained by the two methods have high reliability, and can effectively predict the formation fracture system, and ultimately guide the exploration and development deployment of fractured oil and gas reservoirs (Bouchaala et al. 2019). There is an obvious step between the cavity section and the fracture section, which indicates that the diameter of the pore throat of the connected pores and the width of the fracture have abrupt changes, rather than gradually becoming smaller. There is also an obvious step between the pore section and the pore section, which also shows that the pore throat diameter of the connected pores and the pore throat diameter of the connected pores have a sudden change in size. The fracture tectonic stress field analysis method is based on the theory of tectonic mechanics, using the geometric information and lithology information of the formation to estimate the stress field of the formation, including the curvature tensor, deformation tensor and stress field tensor of the formation, so as to obtain the distribution results of principal curvature, and principal stress are used to predict favorable parts for fracture development.

The existence of fractures causes the physical and chemical properties of the medium to change with different azimuths. It is called azimuth anisotropy in earthquakes, and the direction parallel to and perpendicular to the fractures is called the main anisotropic azimuth. By comparing the parameter change pattern of longitudinal and share wave impedance, it can be seen that the azimuth difference of shear wave impedance is obviously greater than that of primary wave impedance, and the effect of using shear wave impedance to predict fractured formation is better than that of primary wave impedance. Therefore, the fracture strength, density, and strike parameters of fractured reservoirs can be predicted by analyzing the shear wave impedances of different azimuths. The azimuth longitudinal and share wave impedance ellipse analysis shows that the impedance of each azimuth and share wave is quite different, so the fractured formation can be predicted based on the azimuth and share wave impedance analysis [26]. Due to the complex geological structure, the seismic waves repeatedly move underground to form a chaotic whole, so we can regard it as a chaotic time sequence, because the data at a certain point in space will undergo multiple superimpositions to produce a similarity. When the reservoir is measured, the value of the capacity dimension suddenly increases because the amplitude changes drastically with the frequency; at the same time, if the detected layer is not the target layer, because the amplitude does not change with the frequency. The value of the capacity dimension does not change much, so the capacity dimension can be applied to actual oil and gas production and development.

Conclusions

This paper takes the marginal subsags in the Jiyang Depression, Eastern China as an example to study t the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles. This study proposed the equivalent geological model and elastic

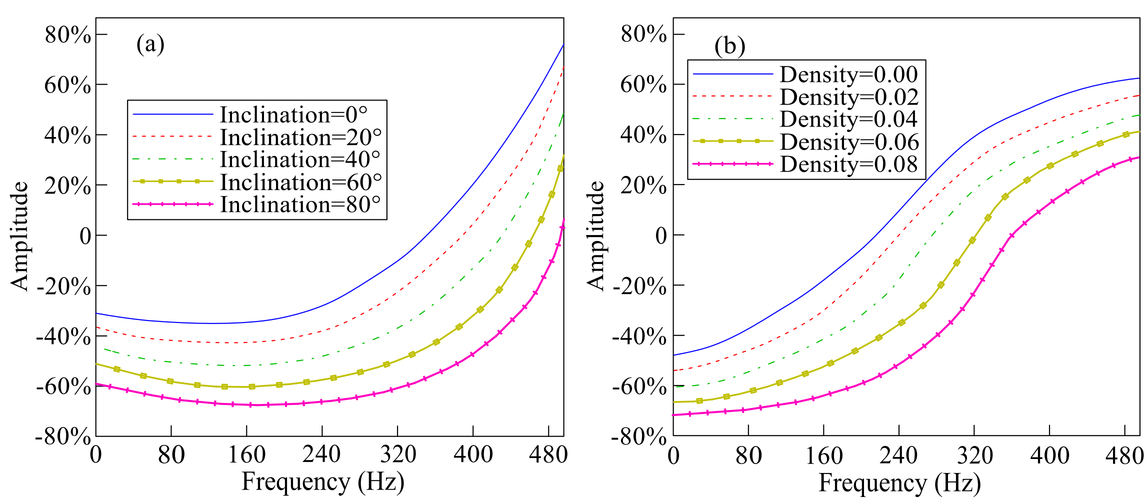

Fig. 8 Relationships between seismic wave amplitudes and frequencies at different fracture inclinations (a) and fracture densities (b)

characterization parameters for the fractured marlstone reservoirs in study area, analyzed the seismic response patterns, anisotropy characteristics, and seismic wave-field distribution of the marginal subsags in the Jiyang Depression, discussed the influences of fracture filling fluid, density, inclination, orientation, and layer thickness on the characteristics of seismic wave propagation in fractured marlstone reservoirs, and finally explored the shear wave splitting phenomenon and the exploration and development significance of the seismic wave propagation in fractured marlstone reservoirs. The resolution of the tuning profile of the main frequency after the spectral decomposition process is improved, and the physical properties of the underground rock layer appear more clearly. The greater the fracture density, the more obvious the difference between the high and low frequency limits; the greater the porosity, the greater the velocity difference, indicating that the greater the porosity, the more fluid can pass through the fracture and between the pores. Combined with the results of the forward modeling of the model, it is inferred that the black bands with poor coherence may be the response characteristics of fractures or small fractures. The effective absorption coefficient is inversely proportional to the cube of the wave speed and the phase velocity appears in a release interval with frequency. When the rock formation wave speed changes slightly, the absorption attenuation information is more obvious than the wave speed change, and its sensitivity far exceeds the sensitivity of amplitude, frequency, and velocity information relative to lateral changes. In the same lithology, different saturations and different pore fillings, the effective absorption coefficient of oil-saturated oil and gas will increase several times compared with water-bearing conditions. The study results show that factors such as fracture filling fluid, density, inclination, orientation, and layer thickness have serious affection on the seismic wave propagation, making it appear anisotropic, dual-phase characteristics, and also causing phase velocity and attenuation changes. The study results provide a reference for further researches on the characteristics of seismic wave propagation in fractured marlstone reservoirs based on mechanical principles.

Declarations

Conflict of interest The author(s) declare that they have no competing interests.

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