Identification and distribution of fractures in the Zhangjiatan shale of the Mesozoic Yanchang Formation in Ordos Basin

Hui Shi¹, Xiaorong Luo¹, Hui Xu¹, Xiangzeng Wang², Lixia Zhang², Qingchen Wang¹, Yuhong Lei¹, Chengfu Jiang², Ming Cheng¹, and Shan Ma¹

Abstract

The natural fractures in mud or shale directly affect the quality and efficiency of shale gas reservoirs, and fracture identification and prediction play an important role in drilling shale gas wells and making plans for reservoir stimulation. We adopted ant tracking technology for 3D poststack reflective seismic waves to identify the size and distribution of high-angle structural fractures in the Zhangjiatan shale of the Yanchang Formation in the Ordos Basin, which is a typical continental shale. The parameters for ant tracking fractures are extracted from the investigation on outcrop, cores, and image logs. The prestack seismic diffractive wave imaging technique for the super-resolution identification of mid- and small-scale breakpoints can be used as the constraint conditions for ant tracking. The identified result of high-angle fractures was validated by the image logging and drilling gas logging results. The geologic and logging data indicate that the Zhangjiatan shale is mainly characterized by high-angle fractures and a smaller number of low-angle fractures. The fractures mainly trend in the near east–west direction, followed by the near north–south direction, and a small amount of fractures in the north–northeast and northwest–west directions. The average density of structural fractures is relatively low, but the cemented rate is only 15.7%, and most structural fractures maintain an open state. The identified and predicted structural fractures are mainly distributed in the southeast of well LP180 and south of well LP179. The higher gas shows from actual well drilling in shale directly correspond to the density and intensity of high-angle fractures rather than the matrix gas abundance in shale, which indicates that the sweet spot of gas production in shale is clearly controlled by structural fractures.

Introduction

Natural fractures are considered as the fractures in a formation prior to drilling (Nelson, 2001). The development of natural fractures in the mud or shale layer directly affects the quality and efficiency of a shale gas reservoir, and the identification and prediction of natural fractures are essential for the exploration and deployment of shale gas (Hill and Nelson, 2000; Curtis, 2002; David et al., 2004). Compared with sandstone, shale is easier to perform a viscoelastic deformation with relatively stronger anisotropy and more complicated fractures (Laubach et al., 1998, 2009; Yang and Aplin, 2010; Sayers, 2013). Thus, it is more difficult to identify and predict fractures quantitatively in shale than in sandstone (Laubach et al., 1998, 2009; Yang and Aplin, 2010; Sayers, 2013).

The Zhangjiatan shale in the Chang-7 member of the Triassic Yanchang Formation in the Ordos Basin is a typical lacustrine mud or shale layer, and rich shale gas has been estimated in it since a commercial gas well was drilled successfully for the first time in 2011 (Wang et al., 2014). Compared with marine shale, lacustrine shale has more silty laminae, which are generally composed of brittle minerals (such as quartz and feldspar) (Cheng et al., 2015; Lei et al., 2015). These minerals give the shale a higher brittleness index and make it easier to induce natural fractures under the same structural stress (Aplin et al., 2006; Day-Stirrat et al., 2008; Gale et al., 2014). However, the lack of a method for predicting fractures in shale severely restricts the understanding of fracture distribution and the exploitation of shale gas in the Zhangjiatan shale.

Generally, structural fractures in the shale mainly contain six types, namely, the high-angle shear fracture, tension fracture, low-angle slip fracture, structural pressure solution fracture, vertical load fracture, and vertical difference load fracture (Ding et al., 2011). But the shale mainly deforms to create ductile shear fractures approx-
imatively perpendicular to beddings in the reservoirs with high brittleness and slip fractures approximately along the beddings in the ones near the sandstone layer (Abouelrash and Slatt, 2012). The present methods for fracture prediction can be roughly categorized into three types (Nelson, 2001): (1) investigating the stress field distribution to roughly summarize the distribution range of structural fractures, (2) adopting a nonlinear theoretical method, such as the fractal theory and neural networks to speculate fractures, and (3) identifying and predicting fractures comprehensively from logging and seismic information.

Previously, the fractures of the Yanchang Formation in the Ordos Basin have been studied (Darby and Ritts, 2002; Zeng et al., 2007; Zeng, 2008; Zeng and Li, 2009; Jiang et al., 2013; Jiang, 2014). At first, dramatic tectonic activities and large-scale fracture system are absent in this basin because the basin has experienced continuous subsidence, overall uplift, and weak folding. The subtle faults in the Mesozoic are difficult to identify by traditional seismic reflection waves (Darby and Ritts, 2002). It also has difficulty in predicting fractures using the tectonic stress field and nonlinear theory for the absence of a dominant fault system. Nonetheless, the fracture observations on outcrops and in wells (Zeng et al., 2007; Zeng, 2008; Zeng and Li, 2009; Ma, 2016) demonstrated that high-angle structural fractures were dominating in the Yanchang Formation instead of low-angle structural fractures or diagenetic fractures. High-angle structural fractures seem to play an important role in fluid connectivity (Zeng and Li, 2009). Moreover, the lithologic heterogeneity (i.e., sandstone, shale, silt laminae) in the Yanchang Formation is strong, and there are considerable differences for every type of lithology in the development degree, scale, and distribution of structural fractures under the approximate structural stress (Jiang et al., 2013; Jiang, 2014; Ju et al., 2015; Ma, 2016). Previous studies on predicting structural fractures in the Yanchang Formation of the Ordos Basin (Zhou et al., 2007; Zhu, 2013) usually ignored the subtle faults and lithologic heterogeneity, and the fracture prediction results seemed to be imprecise. Therefore, to accurately identify and predict structural fractures only in the shale has become the key issue for the shale gas or oil in the Zhangjiatan shale, in view of the different fracture responses between shale and sandstone.

Traditional processing and imaging technologies for seismic waves often suppress the information of subtle structural and lithologic bodies that are comparable with or smaller than the main seismic wavelength. The information of such subtle geologic bodies (such as small fault, pinch-out, scatter, discontinuous body) may, more or less, be recorded or reflected in the diffractive waves, which have a super-resolution and can be used to interpret subtle structural breakpoints (Zhao et al., 2011). Meanwhile, ant tracking in 3D seismic waves is currently one of the most common technologies for effectively identifying and predicting structural fractures (Drigo et al., 1996; Miller et al., 2012). The “ant” moves forward along the possible faults and fractures according to detecting the differences between the seismic amplitudes and phases, and it stops when the faults and fractures are completely delineated. This fracture detection technique based on the anisotropy of seismic data, combined with the identification of structural breakpoints from the prestack diffractive waves, can satisfy the fracture prediction in shale.

In this paper, we first investigated structural fracture information from the outcrop, core, and image log of the Zhangjiatan shale, and then we attempted to identify the subtle faults or fracture points using the prestack seismic edge diffractive wave imaging technique. Under the constraints of the identified fracture information and breakpoints, we applied ant tracking technology for the poststack reflective seismic wave to predict the distribution and development degree of structural fractures in the Zhangjiatan shale, thereby providing the basis for sweet spot prediction and reservoir stimulation of shale gas.

Geologic background

The Ordos Basin is a multicycle sedimentary cratonic basin with steady subsidence, overall uplift, and weak folding. The regional structure is simple and generally presents as a large west-dipping monoclinal slope (Yang et al., 2005; Zou et al., 2013). The study area is located in the southeast of the basin (Figure 1). The Chang-7 member in the Yanchang Formation is the most important Mesozoic hydrocarbon source rock in the basin, and it is also an important target stratum for shale oil and gas exploration (Tang et al., 2014; Wang et al., 2014; Lei et al., 2015). The total thickness of the Chang-7 member is approximately 30–100 m, including two lithologic sections. The lower section is the Zhangjiatan shale, which is dominated with dark or gray shale interbedded with thin, fine-grained sandstone. The upper section is characterized as fine-grained sandstone with gray shale. The overall sedimentary environment presents a freshwater-brackish and semideep to deep lake during the maximum flooding surface period (Ji et al., 2014). The organic matter types in the Zhangjiatan shale are I and II. The total organic carbon (TOC) content is generally 0%–14%. The $H$ index is generally 50–255 mg/g, with an average of 178 mg/g. The $S_1$ value is in the range of 0.03–9.6 mg/g, with an average of 3.1 mg/g, and the $S_2$ value is 0.1–23.4 mg/g, with an average of 8.2 mg/g. The average $T_{max}$ is 450°C, and the maturity of the organic matter ($R_o$) is 0.7%–1.3%, which corresponds to the oil-generation window (Ji et al., 2014; Tang et al., 2014; Wang et al., 2014; Liu et al., 2015).

In the study area, the current direction of maximum horizontal principal stress for the Yanchang Formation, as measured by borehole breakouts, hydrofracturing and induced fractures, is 60°–80°, and the magnitude of maximum horizontal stress recorded by acoustic emission is in the range of 20.3–60.01 MPa. There is a standard linear correlation between the current maximum principal stress and the burial depth (Zeng and
Li, 2009; Zhou et al., 2009). The production history in the Yanchang sandstone reservoirs indicates that the wells were drilled in a square inverse nine-point well pattern and the long diagonal is parallel to the direction of maximum principal stress, which can increase the length and scale of artificial fractures during hydraulic fracturing. It is conducive to improving the single well production and primary oil recovery efficiency (Zeng et al., 2007; Zeng and Li, 2009).

**Fractures observed on outcrops**

We observed approximately 852 structural fractures in the Chang-7 members of the Yanhe Outcrop in the southeastern Ordos Basin. (The location is shown in Figure 1c.) We found that there are obvious differences between the structural fractures in the Zhangjiatan shale and the ones in the interbedded sandstones (the lower section). High-angle (with a dip angle of 70°–90°) fractures, which dominantly trend in the near east–west direction (approximately 265°–275°), were mainly found in the Zhangjiatan shale. The north–south-trending (approximately 0°–20°) high-angle fractures nearly perpendicular to the east–west-trending fractures have developed in some local regions (Figures 2 and 3a), and the quantity of fractures in the north–northeast and northwest–west directions is relatively slight. It differs with the fracture developing in the upper sandstone, the fractures in which are mainly in the northeast–east.

**Figure 1.** (a) Map showing the Ordos Basin in central China, (b) tectonic map of the Ordos Basin showing the study area located in the Yishan slope, and (c) the isopach map of top Zhangjiatan shale in Yanchang Formation in the study area.

**Figure 2.** (a) Photographs of structural fractures in the Zhangjiatan shale of Yanhe Outcrop displaying the high-angle and low-angle network fractures, (b) the high-angle shear fractures in the black shale, (c) the near east–west-trending and near north–south-trending conjugate fractures, and (d) the local near north–south-trending fractures. The dip angles of the near east–west fractures and near north–south are close to 90°.
(approximately 55°–65°) and northwest–west (approximately 270°–280°) directions (Zeng and Li, 2009; Ma, 2016). In addition, on the top of the shale layer near the sandstone layer, more low-angle (approximately 1°–10°) slip fractures were commonly observed, which indicates that there might be more low-angle fractures in the sandstones than in the shales (Figure 2a).

The spacing of high-angle structural fracture in shale from outcrop ranges from 10 to 120 cm (Figure 4a and 4b), and the average spacing of the near east–west-trending and near north–south-trending fractures are the same at approximately 60 cm. The fracture spacing index (FSI) is the slope of the linear function between the fracture spacing and the mechanical layer thickness, which is usually used to characterize the strength of fracture development in rock layers with different thicknesses (Jiang, 2014). In the studied area, the near east–west-trending and near north–south-trending FSIs in the Zhangjiatan shale are 1.15 and 0.45, respectively, (Figure 4c), indicating that the near east–west-trending fractures develop more dominantly than the near north–south-trending fractures in the shale layer.

**Subsurface fractures**

**Fractures observed on cores**

We investigated nearly 500 m cores from the Zhangjiatan shale of eight shale gas wells (namely, the wells in Figure 1c) in the study area. Except for the diagenetic fractures parallel to the bedding (Figure 5a), a total of 120 natural structural fractures were identified. Approximately 67% are high-angle fractures (70°–90°) (Figure 5b), and low-angle fractures (Figure 5d) account for approximately 33%.

The dip angle of high-angle fractures is generally greater than 80°, and some high-angle fractures are half or fully cemented by sparly calcite (Figure 5b and 5c). Microscopic observations suggest that the cement in the high-angle structural fractures is often dissolved to form the secondary dissolution pores (Figure 5c). The proportion of fractures cemented with calcite (Figure 5b and 5e) is less than 42%, and traces of oil and gas migration were found in approximately 12% of these fractures (Ma, 2016).

The low-angle fractures should be caused by frictional slip along the bedding surfaces. Traces of calcite cement can be seen on the fracture surfaces (Figure 5d), and the calcite crystals are dislocated by subsequent compressive structural effects, which created regular secondary microfractures in the calcite cements (Figure 5e).

**Fracture observed on image log**

The use of logging data is one of the most direct and effective methods for identifying and characterizing subsur-
face fractures. In particular, borehole resistivity imaging logging can not only identify fractures but it can also determine the extension direction and occurrence of fractures, and it can thoroughly reflect information on subsurface fractures (Rajabi et al., 2010). In the study area, borehole resistivity imaging logging was performed for eight appraisal wells (Figure 1c) using the STAR-II resistivity scanning device. We chose the resistivity imaging logging data of seven wells near the seismically explored blocks for identifying underground fractures in the Zhangjiatan shale, and well Yanye22 in the seismically explored block was used as the test well for the validation of the seismic data for fracture identification.

The resistance imaging log interpretation in the study area indicates that a total of approximately 70 high-angle structural fractures were identified from approximately 457 m image logging in the Zhangjiatan shale, and the average fracture density was 0.15/m. There were 59 high-conductivity fractures, accounting for 84.3% of the total structure fractures, indicating that most high-angle structural fractures are not filled by cements. The main trending of the high-angle structure fractures in the shale, as interpreted by logging, is near east–west, and the dip angle was approximately 50°–90° (Figures 3b and 6) with a main dip angle distribution of 70°–90°, which is largely consistent with the field outcrop observation results (Figure 2).

Fractures detection with 3D seismic waves

Edge diffractive wave imaging

At present, only one small block of data, which covers an area of approximately 10 × 8 km, has been deployed for 3D seismic survey in the southeast of the basin (Figure 1). In the district, a total of 12 wells (e.g., wells Yanye3, Yanye11, Yanye6, Yanye8, Yanye22, LP178, LP180, etc.) have been completed (Figure 7). In this paper, we adopted the prestack seismic edge diffractive wave imaging method (Zhao et al., 2011) and we used the diffraction coefficient derived from the law of energy flow conservation to calculate the dynamic characteristics of the diffractive wave field. The edge diffractive wave processing result for the prestack seismic dataset of the Zhangjiatan shale is shown in Figure 7, in which the blue patches represent the breakpoints that can generate edge diffractive waves. By analyzing the distribution and combination features of breakpoints, it is found that there is an obvious distribution of breakpoints in two regions, near well LP180 and southeast of well LP179, indicating that these regions have a dense fracture development in the shale.

Ant tracking of fractures

The main frequency of the poststack seismic waves in the study area is 30 Hz, which is suitable for identifying and predicting the high-angle fractures. These structural fractures usually have a relatively larger size than the diagenetic fractures, such as the bedding fractures, grain edge fractures, and intragrain fractures. In view of diagenetic fractures having a limited role in the fluid activity of the Yanchang Formation (Zeng and Li, 2009), we mainly identified and predicted the high-angle structural fractures in the Zhangjiatan shale. The specific procedures included the following: (1) applying the structure-oriented filtering processing to the poststack seismic data set to enhance the continuity of seismic reflection wave amplitude and (2) calculating the ant attribute cube combined with the information about

Figure 5. (a, b, and d) Photographs of fracture cores and (c and e) corresponding thin section from Zhangjiatan shale, showing (a-c) the high-angle structural fracture and (d and e) the low-angle structural fracture in shale. (a) An open high-angle fracture was met at the depth of 1286–1286.5 m of well Yanye22 and (b) the high-angle fracture in 1310.2–1310.5 m of well Yanye22 is (c) partially cemented by calcite. (d) A low-angle fracture on core at the depth 1277.3–1277.4 m in well Fuye1 is completely cemented by calcite, and (e) the calcite cements are dislocated by subsequent compressive structural effects.
structural fractures from outcrops, cores, and image logs for the adjustment parameter.

In particular, the focus of the parameter adjustment was to determine the ranges of the initial boundary, search step, and stop threshold. Using the extracted information about high-angle structural fractures above and below the ground as the constraint conditions, we calculated the ant attribute cube of the Zhangjiatan shale in the study area from the poststack seismic reflection waves. The characterized fractures are extracted in the shale section, as shown in Figure 8.

In comparison with the imaging result identified by the prestack edge diffractive wave in Figure 7, we found that the fracture responses obtained by the two methods are largely consistent. The high-angle fractures are mainly concentrated in the regions near well LP180 and southeast of well LP179 (Figures 7 and 8).

Validation of the results
According to the work design, we used resistivity imaging logging of well Yanye22 and the current drilling gas loggings in the seismic survey area to validate the aforementioned fracture identification and prediction results. For well Yanye22, the resistivity imaging log-

**Figure 6.** Image log profile of the Zhangjiatan shale in well Fuye3 (1273.0–1288.0 m) showing more conductive fractures (blue tadpole) and less resistive fractures (light blue tadpole).

**Figure 7.** The prestack edge diffractive wave imaging of the Zhangjiatan shale in the southeastern Ordos Basin showing two regions with abundant breakpoints (dark blue patches), southeast of well LP180 and south of well LP179.

**Figure 8.** Fracture imaging by ant tracking in 3D seismic of the Zhangjiatan shale in the southeastern Ordos Basin obviously showing that two regions, namely, southeast of well LP180 and south of well LP179, respectively, have more fractures than other regions.
ging indicated that the sandstone section in the upper Chang-7 member mainly presents as high-angle (60°–80°) structural fractures, and the trending direction is near east–west, whereas there are only sparse structural fractures in the Zhangjiatan shale (Figure 9).

Based on our previous work (Cheng, 2016), we comprehensively evaluated the matrix gas abundance for the rock segment of the Chang-7 member in the study area (Figure 10) by adding some new data of the TOC content, logging response, and gas saturation of the Zhangjiatan shale obtained in wells. Figure 10 indicates that the regions with the largest abundance of shale gas are located to the north of well Yanye11 and south of well Yanye22 in the 3D seismic survey area, and the matrix gas abundance is approximately 4 × 10⁸ m³/km². These regions clearly do not coincide with the fracture development regions (southeast of well LP180 and south of well LP179). However, the drilling gas logging displays in the development area seem consistent with the structural fracture development regions. The average gas logging display of the Zhangjiatan shale (e.g., wells Yanye16 and Lp179) reaches approximately 50% and 40%, whereas the average gas logging display for wells Yanye11 and Yanye22 with less fracture development in the shale layer is approximately 10% and 20% (Figure 10). Such a phenomenon suggests that the sweet spots of the Zhangjiatan shale in the study area are mainly controlled by the development of high-angle fractures.

Discussions

In view of the subtle fault system and strong lithologic heterogeneity, there are some problems in identifying and predicting natural structural fractures in the Yanchang Formation of the southeastern Ordos Basin. Through the aforementioned work, ant tracking technology seems suitable to accurately identify and predict high-angle structural fractures in the Zhangjiatan shale. This method should effectively extract the information about the fracture occurrence, dimension, spacing, and cementation degree etc., based on fracture investigations from outcrops, cores, and resistivity image logs. The edge diffractive wave imaging by 3D prestack seismic data appears also effective for identifying the subtle structural breakpoints. However, this method only illustrates the rough domains of the fracture regions, so that the results can be used as constraint conditions for ant tracking technology. The prediction results of high-angle fractures are then detected to be consistent with the image log interpretation of well Yanye22 and with the gas logging shows of 11 wells in the seismic survey area. It indicates that the integrated method that using ant tracking restrained by information from outcrop, image log, and edge diffractive wave imaging from 3D prestack seismic data to predict fractures in shale is achievable, at least in the study area.

The identification and prediction results for the high-angle fractures in the Zhangjiatan shale are largely consistent with the sweet spots indicated by the actual drilling gas logging, instead of the matrix gas abundance that corresponds to high TOC content, logging, and gas saturation in reservoirs. This suggests that the sweet spot for shale gas in the study area is mainly controlled by the density and strength of high-angle fractures instead of the matrix gas abundance. It conforms to Figure 9.

![Figure 9. Image log for the Chang-7 member in well Yanye22 showing scarce fractures in the Zhangjiatan shale, indicating that the interpretation agrees with the results (Figure 8) from ant tracking fractures in the 3D seismic wave and from edge diffractive wave imaging (Figure 7).](https://library.seg.org/)
the common recognition that the development of natural fractures in shale aids the growth of a free-state gas volume in shale and increases the desorption and total gas content of absorbing natural gas (Curtis, 2002). Although we implemented the identification and prediction of structural fractures in the Zhangjiatan shale in this paper, the resolution of seismic wave data and the thickness of the shale layer are the main factors controlling the prediction accuracy. The biggest problem is neglecting some small fractures. Because the overall thickness of the Zhangjiatan shale is relatively thin, the response from seismic reflection waves may be not strong enough to reflect small-scale structural fractures such as diagenesis fractures in the shale layer. Therefore, the conditions of fracture development in shale as predicted in this paper could not include some structural fractures at the small scales, despite that those microfractures may have a small influence on the fluid flow. To achieve an absolutely accurate prediction of structural fractures in shale, it is necessary to further strengthen the methods and techniques for the acquisition and processing of seismic wave signals for mud-rich strata.

Conclusions

In this paper, we investigated the structural fractures in the Zhangjiatan shale of the Chang-7 member in the southeastern Ordos Basin from outcrops, cores, and image logs to extract basic information about fractures, and we identified and predicted the distribution of fractures in shale by ant tracking technology, which was constrained in the basic information from fracture investigation and the edge diffractive wave imaging result of 3D prestack seismic. The following conclusions can be drawn

1) The structural fractures of the Zhangjiatan shale in the study area are mainly high-angle fractures (with a dip angle of 70°–90°) with a smaller number of low-angle fractures (<50°). The trending of fractures is mainly the near east–west direction, followed by the near the north–south, and there are few fractures in the north–northeast and northwest–west directions. The proportion of cemented fractures relative to total fractures from the cores is less than 42%, and high-conductivity fractures account for 84.5% of the total structural fractures according to the imaging logging, indicating that the majority of structural fractures remain in an open state.

2) An integrated method that uses ant tracking restrained by information from the outcrop, image log, and edge diffractive wave imaging from 3D prestack seismic to predict fractures in shale was applied in the study area, and the results have been verified by the image log. This method can be generalized in other shale areas with 3D seismic data.

3) The value of gas show logging increases with the density and intensity of structural fractures and does not conform to the matrix gas abundance in shale, which suggests that the gas production’s sweet spots should be primarily influenced by the high-angle fractures in shale.

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Biographies and photographs of the authors are not available.