Simulation of paleotectonic stress fields within Paleogene shale reservoirs and prediction of favorable zones for fracture development within the Zhanhua Depression, Bohai Bay Basin, east China

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ABSTRACT

Objective: Tectonic fractures are the most important reservoir spaces within shale reservoirs and can significantly improve the permeability of a reservoir, the development and distribution of these fractures are controlled by paleotectonic stress fields. An important hydrocarbon reservoir is hosted by a Paleogene shale unit within the lower section of the third member of the Shahejie Formation (Es3) within the Zhanhua Depression of the Bohai Bay Basin, east China. Industrial-level oil and gas production has been obtained from over 30 wells with the highest single well production of 93 t/d, indicating the large oil and gas potential of these reservoirs in the Zhanhua Depression.

Methods: The data obtained from cores, logs, and drilling in the Zhanhua Depression can be used to identify the processes involved in the development of such tectonic fractures. In this study, these data were combined with additional acoustic emission and rock mechanics data to identify the effects of faulting and lithological variations on the development of fractures using a finite element method (FEM) stress analysis approach that simulated paleotectonic stress fields during the late Dongying stage, the period of time when the majority of the fractures developed. Estimations of rock failure criteria and comprehensive indexing of rupture rates for tectonic fractures were undertaken to determine the quantitative development of fractures and to predict favorable zones for fracture development.

Results: Tectonic fractures within the shale reservoir in the lower part of the Es3 unit include both tensional and shear fractures, these fractures are generally unfiled or half-filled. The NE-SW strike of these fractures is consistent with the orientation of the present stress field, meaning that these fractures were high-priority targets during initial well targeting. Tectonic fractures can be identified during logging by increased resistivity (R2.5), increased acoustic time difference (AC) values combined with cycle skip of the peaks, and highly variable but generally elevated gamma ray (GR) values. Fractures can also be directly identified, and fracture parameters can be determined using Formation MicroScanner Image (FMI). The magnitude of the maximum principal stress during the major period of fracture development within the Zhanhua Depression was 53.2 MPa, and the paleotectonic stress field was controlled by the location of fault zones. In contrast, areas without fractures have stress fields that were influenced by lithological variations, leading to the development of high stress fields in areas with rocks containing high concentrations of carbonate.

Conclusion: Fracture development is controlled by tectonic stress fields and fractured areas are generally located between fault zones, at the intersection of faults, in areas when fault orientations change, and at high stress areas near fault tips. The present results regarding predictions of the locations of fractured areas are consistent with the location of producing oil and gas wells.

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1. Introduction

A general global increase in the demand for energy has occurred since the turn of the 21st century, with 80% of this demand met by oil and natural gas resources (IEA, 2010). However,
current levels of oil and gas exploration and production are insufficient to meet this huge demand for energy. This has led to an increase in demand for new fields of oil and gas exploration. A significant amount of exploration has focused on the Zhanhua Depression, east China, leading to the identification of industrial-level oil and gas production from more than 30 wells that target shales within the lower part of the Es3 unit. These shales are similar to typical source rocks in traditional oil and gas plays, rather than typical reservoir rocks. The fact that these shales, and other examples from around the world, are important hydrocarbon reservoirs has meant that this type of reservoir has become the focus of a new type of oil and gas exploration. A number of characteristics of shale-hosted oil and gas reservoirs have been identified (Guan et al., 1995; Curtis, 2002; Jarvie et al., 2007; Kinley et al., 2009; Ding et al., 2013) and are summarized here: (1) shale hydrocarbon reservoirs are typically developed within organic-rich source rocks dominated by dark-colored shales; (2) these shale reservoirs typically have low porosity and permeability (Li, 1997; Zeng and Li, 2009; Jiu et al., 2013), as exemplified by the shale reservoir within the lower part of the Es3 unit of the Zhanhua Depression, a unit with an average porosity of 5.51%, and an average permeability of < 10 md; and (3) the majority of reservoir space and seepage channels are provided by fractures, especially tectonic fractures, which can effectively improve the permeability of shale reservoirs and influence well deployment and the development planning of shale oil and gas reservoirs (Corbett et al., 1987; Nelson, 2001; Peggy and Michele, 2001; Zhang and Sanderson, 2002; Shedid, 2006; Ahr, 2008; Zeng et al., 2013). In particular, shales within the Zhanhua Depression contain significant amounts of brittle carbonate and quartz, and only minor amounts of clay minerals, meaning that the late tectonic movements can more readily produce tectonic fractures. The development and distribution of tectonic fractures are generally controlled by local tectonic stress fields (Mckinnon and

Fig. 1. Location of the study area. (a) Maps show the elementary structural features of Zhanhua Depression and (b) the north–south structural section with the location is shown in (a).
Barra, 1998; Tuckwell et al., 2003; Ding et al., 2012). One of the important methods used in shale oil and gas reservoir exploration and development is studying changes in the tectonic stress field, determining the processes involved in fracture development, and then forecasting favorable zones for oil and gas accumulation. The formation mechanisms, controlling factors, and methods of identification of fractures within the lower part of the Es3 shale reservoir have previously been investigated within the Zhanhua Depression (Yuan, 2003; Xu et al., 2003; Zhi et al., 2004). However, a systematic understanding of the paleotectonic stress field during the main period of fracture development and the distribution of fractures is still lacking. Here, we discuss the development of these tectonic fractures, the main period of fracture development, and logging methods that can be used to identify fractured areas. In addition, we report the data of acoustic emission and rock mechanics, the results of numerical finite element method (FEM) simulation of the shale's paleotectonic stress field, and the analyses of favorable areas for fracture development. These new evidences can provide a geological basis for shale exploration and the development of oil and gas reservoirs.

2. Geological setting

The Zhanhua Depression is located in the southeast of the Mesozoic–Cenozoic rift-related Bohai Bay Basin (Zhang et al., 2009; Hao et al., 2010) (Fig. 1a). The structural development and sequence stratigraphy of the basin mean that the post-Tertiary tectonic evolution of the Bohai Bay Basin can be divided into two stages: a rifting stage (from Eocene to Oligocene) and a post-rifting stage (from Miocene to Pliocene) (Hou et al., 2001; Shi et al., 2004; Qi and Yang, 2010; Zhou et al., 2012). The rifting stage comprises three Paleogene units (Ek, Es, and Ed) and has a stratigraphy that is generally controlled by boundary faults. The post-rifting stage comprises a tectonic sequence of Neogene and Quaternary sediments that occupies the entire basin, and a regional unconformity separates the Paleogene and the Neogene. The present-day Zhanhua Depression consists of a duplex half-graben rift that is influenced by NE–SW and ENE–WSW striking extensional, strike-slip faults. These faults formed multiple low uplifts and half-grabens that are faulted in the north and gentle slope in the south. Tectonic units in the study area can be divided from south.
to north into the Chenjiagou uplift, the Luojia nose structure, the Sikou sag, the Yidong fault zone, and the Yiezhuang uplift (Fig. 1b). The areas examined in this study include the Bonan and Sikou sags and the Luojia nose structure zone within the Zhanhua Depression. The area is dominated by NE–SW, NNE–SSW and WNW–ESE trending faults that developed during two separate tectonic events: during the Es4–Es3 and Late Dongying stages (Zhu et al., 2005).

Multiple lacustrine organic-rich shales have been deposited in the Zhanhua Depression since the Paleogene. Of these shales, the dark shale in the lower part of Es3 is the most important for hydrocarbon exploration (Fig. 2). This shale unit consists of interbedded dark gray and gray marls, calcareous shales, lime-rich mudstones, dark gray mudstones, and shales with minor silty mudstones that formed in a semi-deep to deep lake environment. Sandstones, pebbly sandstones, and conglomerates are present at the edge of the depression, and were formed in nearshore subaqueous fan and fan delta environments. The lower part of Es3 unit was deposited during a stable post-extensional period during subsidence of the lake basin and expansion of the lacustrine environment, including deepening of the water within the lake. In addition, a significant amount of terrigenous or aquatic organic matter was deposited in this deep lake environment, favoring the formation of dark-color shales. At the same time, the high rate of deposition in this area led to rapid burial of organic matter within a persistently reducing environment that provided the necessary conditions for the preservation of organic matter.

3. Samples and testing

A total of 25 samples of the lower part of Es3 were collected from the L69 well’s drill cores in Zhanhua Depression for rock mechanics and acoustic emission analysis. All the samples were formed into cylinders with diameters of 2.5 cm, heights > 5.0 cm, and non-parallel and non-perpendicular errors of < 5 μm and < 0.1°, respectively, with a surface smoothness of greater than class 5 or 3.2 μm.

Sixteen samples were used for rock mechanics analysis. Rock densities were determined through density analysis. Rock tension strength, Poisson’s ratio and Young’s modulus values were determined by a uniaxial compressive test (Table 1). The applicable standard was part 9 of GB/T 23561.7-2009: methods for determining the triaxial strength and deformation parameters of coal and rock. All analyses were undertaken at the Civil Engineering Laboratory of Beijing University of Science and Technology, China.

Paleotectonic stress values were determined using acoustic emission testing of nine samples at the Geomechanical Research Institute Laboratory of the China Geology Academy, Beijing, China. Data for AE ratio (acoustic emissions/s) vs. applied load graphs was recorded for primary pressure (first loading) and secondary pressure (reloading under set conditions) (Ding et al., 2012). Loads were applied to the nine prepared core test specimens using a WE-30 300KV universal testing machine with the precise of ≤ 1%. This device can assess stresses from paleostress periods and reveal the maximum effective paleostress that have been experienced by the examined strata (Ding and Shao, 2001).

4. Characteristics and timing of formation of tectonic fractures

4.1. Characteristics of tectonic fractures

Fractures in shale reservoirs can form important reservoir spaces and seepage channels. Analysis of cores observation of shales in the lower part of the Es3 unit has identified that tectonic fractures are the most important type of fracture within this unit. These tectonic fractures included tensional and shear fractures. Tensional fractures have oblique contacts with bedding planes within the sediments (Fig. 3a). These fractures were usually open, and were subsequently filled with minerals and asphalt. In contrast, shear fractures were stable after formation, leading to the formation of long fractures (Fig. 3b and c). In addition, micro-fractures were identified in drill cores (Fig. 3d), with throws of 0.5–5 mm. These faults are consistent with regional structures that produced normal faulting during extension.

Table 1

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Diameter D (mm)</th>
<th>Height H (mm)</th>
<th>Failure load P (kN)</th>
<th>Compressive strength e_c (MPa)</th>
<th>Elastic modulus E (GPa)</th>
<th>Poisson's ratio μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocky mudstone</td>
<td>24.80</td>
<td>54.63</td>
<td>15.84</td>
<td>29.24</td>
<td>37.95</td>
<td>0.360</td>
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<tr>
<td>Calcareous laminae shale</td>
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<td>60.63</td>
<td>22.53</td>
<td>42.00</td>
<td>37.15</td>
<td>0.396</td>
</tr>
<tr>
<td>Marl</td>
<td>24.80</td>
<td>59.85</td>
<td>32.48</td>
<td>60.56</td>
<td>20.31</td>
<td>0.350</td>
</tr>
<tr>
<td>Calcareous shale</td>
<td>24.78</td>
<td>60.85</td>
<td>19.59</td>
<td>36.65</td>
<td>34.96</td>
<td>0.400</td>
</tr>
</tbody>
</table>

* Abnormal data that do not participate in the calculation.
Fracture parameters are important in the exploration and development of fractured shale reservoirs. Statistical analysis of fractures within drill core from the lower part of the Es3 unit indicates that these fractures dip angles at 30°–50°, indicating that these fractures are generally inclined fractures that formed during a period of combined tensional and shear stress. The length of tectonic fractures is generally less than 15 cm, with the majority having lengths between 2 and 8 cm (Fig. 4). By detailed observations and statistics of cores fractures from wells L69, L67 and XYS 9, it is believed that the fracture fills vary among the wells, and there is a dominance of unfilled and half-filled fractures, with few completely filled fractures (Fig. 5).

Fracture linear line density is an important indicator of fracture development. Fracture linear line density is defined as the number of fractures per length (Shaw, 2005). The shale fractures in the lower part...
of Es3 are relatively well developed, with a maximum fracture density of 18 m\(^{-1}\) in well L67 and an average of 9 m\(^{-1}\). Fracture widths were estimated using FMI data, yielding fracture widths of 10–100 \(\mu\)m and the maximum visual porosity of fractures reached a maximum of 0.3%, but with the majority of values being 0.09–0.27%. Tectonic fractures generally strike NE–SW (Fig. 6a), although NNE–SSW and WNW–ESE striking fractures are also present. The present-day orientation of maximum horizontal stress within the study area is ENE–WSW (Fig. 6b), similar to the strike of NE–SW striking fractures. This indicates that the NE–SW fractures are the most permeable, and these fractures were also the main targets during the early development and deployment of the hydrocarbon well network in the study area.

4.2. Timing of fracture formation

The lower part of the Es3 unit hosts the majority of fractured shales within the Zhanhua Depression, and consensus has been reached on the timing of fracture development. Ning (2008)
suggested that these fractures formed during the Late Dongying stage. At this period, the area in eastern China was influenced by Indian plate and the Pacific plate and this study area was in dextral strike-slip stress regime (Wu et al., 2004). Wan et al. (2012) concluded that tectonic movement during this stage not only formed a major regional angular unconformity, but also fractures within Paleogene sediments. In addition, Xiang (2008) considered that these fractures were closely related to faulting in the study area. Analysis of the tectonic evolution of this area indicates a high growth index for the syn-sedimentary faults that controlled tectonic fracturing during the late Dongying, indicating significant fault development at this time. The Es3 shales had also undergone consolidation and lithification by this stage, meaning that the majority of fractures developed during the late Dongying.

5. Identification of fractures by logging

Many logging-based methods have been used to identify fractures within sandstone, limestone, and igneous hydrocarbon reservoirs. However, a number of problems still exist in logging-based identification of fractures within shales. Currently, the main method used to identify such fractures is qualitative identification using resistivity ($R_{2.5}$), acoustilog (AC), gamma ray (GR), caliper (CAL), spontaneous potential (SP), and FMI logging (Chen et al., 1988; Lorenz and Finley, 1991; John et al., 2002; Ross and Bustin, 2007; Tong et al., 2012).

Shale fractures within the lower section of the Es3 unit of the Zhanhua Depression can be identified by enhanced resistivity ($R_{2.5}$), increasing AC values with cycle skip of peaks, the presence of negative SP values within stable background values, and elevated but highly variable GR values (Fig. 7).

The combination of high-resolution data with large amounts of geological information and visual imaging means that FMI is an important tool in researching into shale fractures, as it not only enables the determination of the occurrence, orientation, and strike of fractures within shale, but can also provide fracture vectors, including aperture and fracture porosity values (Zhang and Pan, 2012). FMI analysis in the present study area has enabled the identification of changes in tectonic fracture and micro-fault angles (Fig. 8), and has yielded results that correspond well to core observations.

6. Theory and method

6.1. Numerical simulation of paleotectonic stress fields

Stress field research can use tools such as geological analysis, physical modeling, and numerical simulation, including the finite element method (FEM). In this study, the FEM and ANSYS computer software were employed to produce a two-dimensional simulation of the stress field. The basic concept behind FEM is that a geological body can be discretized into finite continuous elements that are connected by nodes. Each element is allocated appropriate geomechanical parameters determined for real rocks. The continuous field function for the region is first transformed into a function at each node that incorporates the basic displacement, stress and strain variables resulting from the applied external forces (Ding et al., 2012). These elements are combined to obtain the tectonic stress...
field over the entire geological body (Zhou et al., 2009; Wu et al., 2009).

6.1.1. Geological units

The Zhanhua Depression underwent multi-stage Mesozoic–Cenozoic tectonic movements that caused tension-shearing faulting but only minor folding, indicating that fracturing within sediments in the study area was fault-controlled. Fracturing of shales within the lower part of the Es3 units occurred during the Late Dongying; given this, we analyzed contemporaneous faulting. Lithology was also a key control on the development of fractures within the shale reservoir (Ding et al., 2011; Mohammed et al., 2012). Consequently, we divided the model based on the carbonate contents of shales in the lower section of the Es3 unit, as intercepted by several wells sunk into laminated calcareous shales, marls, calcareous shales, and blocky mudstones.

These inputs mean that the geological model contained differing zones representing faults, uplifts, and sediments. The scale of the faults meant that the fault zone was divided into first-level and second-level fault zones (the former representing the Yidong fault zone), and the sedimentary zone was divided according to lithology (Fig. 9).

6.1.2. Mechanical model

6.1.2.1. Material properties. During modeling, the geological model was treated as an elastic body with units that had variable rock mechanical properties, such as elastic modulus and Poisson’s ratio. These parameters were determined during rock mechanics testing (Table 1). The processing method used to define the fault zone was fundamental to the outcome of the modeling as it directly affected the results of the numerical simulation. In general, the fault zone is defined as a soft zone with elastic modulus values of 50–70% of the values of the sediments within the model. Poisson’s ratio of a fault zone is larger than Poisson’s ratio of a corresponding normal sedimentary rock stratum, and the difference between these two ratios is typically between 0.02 and 0.1 (Zhou, 2003; Liu et al., 2008).

In addition, elastic modulus and Poisson’s ratio values are related to the complexity of the fault zone, with increasing complexity causing decreasing elastic modulus and increasing Poisson’s ratio values. The first-level fault zone was assigned an elastic modulus value of 16.30 GPa and a Poisson’s ratio value of 0.4, whereas second-level fault zones had an elastic modulus value of 19.52 GPa and a Poisson’s ratio value of 0.385. Uplift areas were assigned elastic modulus and Poisson’s ratio values of 32.59 GPa and 0.376, respectively.

6.1.2.2. Boundary conditions. The boundary conditions within the model include boundary force and displacement boundary conditions. Analysis of the Late Dongying stage tectonic stress field within the study area indicated that the Bohai Bay Basin was undergoing near E–W (100–280°) shortening and extrusion caused by westward subduction of the Pacific Plate and related compressional effects (Wan, 2011). The maximum principle stress is determined by acoustic emission test and the geological condition. In this study area, the most intense and extensive tectonic movement experienced by the third member of the Shahejie Formation (Es3) was Late Dongying movement which was also the timing of fracture formation. Therefore, it is reasonable that a maximum principal stress during the late Dongying tectonic movement was 53.2 MPa (Fig. 10).

Appropriate displacement constraints were applied to the geological model to prevent it from undergoing rigid displacement and rotation, and to facilitate the simulation. The X direction constraint was applied to the left boundary of the model and the Y direction constraint was applied to the lower boundary, leading to boundary conditions where a force...
of 53.2 MPa was applied to the right boundary at a direction of 100°. The maximum principal stress/minimum principal stress ratio value of 2.1 for shallow crust (< 4000 m) (Gao, 2011) enables the minimum principal stress to be calculated, leading to a minimum principal stress force of 25.3 MPa that was applied to the upper boundary at a direction of 10°.

The mathematical and mechanical rules used during the FEM simulation meant that the geological model was meshed with triangular elements and subdivided into a series of nodes and grids forming a model that was divided into 30,717 units and contained 15,448 nodes. The distribution of the maximum and minimum principal stresses, and the shear stress in shales of the lower section of the Es3 unit were determined by a two-dimensional FEM numerical simulation. In this paper, it was provided that compressive stress was negative and a tensile stress was positive.

6.2. Fracture development criteria

Shale drill cores in the lower part of the Es3 unit contain both tensional and shear fractures; these two types of tectonic fracture can be discriminated using the Griffith rupture criterion and the Coulomb–Mohr criterion, respectively (Griffith, 1921; John, 1969; Hardy et al., 1973).

6.2.1. Griffith rupture criterion

A Griffith rupture criterion approach was applied to brittle tensional ruptures, this criterion can be expressed under different conditions in a two-dimensional σ1-σ2 plane.

When σ2 + 3σ1 ≤ 0, the criterion can be expressed as

\[
(\sigma_1 - \sigma_2)^2 + 8(\sigma_1 + \sigma_2)\sigma_T = 0
\]

\[
\cos 2\beta = (\sigma_1 - \sigma_2)/(2\sigma_1 + \sigma_2)
\]

when σ2 + 3σ1 ≥ 0, the criterion can be expressed as

\[
\sigma_1 = -\sigma_T
\]

\[
\sin 2\beta = 0
\]

where σT is the tensile stress strength, σ1 and σ2 are principal stresses, β is the rupture direction, and η is the tensile rupture rate calculated as

\[
\eta = \sigma_T/R_T
\]

where RT is the tensile strength for the rock, RT can be tested by the Brazilian splitting test and the tensile strength for the rock is 2.577–4.648 MPa (Table 2).

6.2.2. Coulomb–Mohr criterion

The basis of the Coulomb–Mohr criterion is that the rupture of rocks is caused by shear failure on a surface, and this shear failure is related to the normal stress δn and the shear stress τn along the surface. The criterion is expressed as

\[
\tau_n = C + \delta_n \tan \phi
\]

where C is the cohesion of the rock, φ is the internal friction angle, and C and φ can be determined by testing. When the normal and shear stress of a surface satisfy Eq. (4), rupturing occurs. Wang et al. (2004) considered that the rate of shear rupturing can be expressed as a principal stress (Wang et al., 2004), which is given as

\[
R = ((\sigma_1 - \sigma_2)/2 + (\sigma_1 + \sigma_2)/2) \sin \phi/C \cos \phi
\]

Sixteen samples were divided into two groups, and cohesion and internal friction angle values were determined by triaxial compression and deformation testing; the results are given in Fig. 11.

6.2.3. Comprehensive rupture rate

Tensional and shear fractures are generally co-developed within shales in the study area. Tectonic fractures are usually developed as a reflection of tensional and shear fractures, both of which have different influences on the development of tectonic fractures. Consequently, the indicator comprehensive rupture rate (I), a quantitative judgment based on the degree of tectonic fracture development, is defined as

\[
I = aI + bR
\]

where a and b are the proportion of tensional and shear fractures, respectively; a and b values of 72.46% and 27.54%, respectively, were used during this study and were derived through a statistical analysis of fractures within drill core. The weighted average of these values yields a comprehensive rupture rate (I). Rocks begin to fracture at values of I ≥ 1, and the greater the value of I, the greater the degree of rupturing, signifying an elevated degree of fracture development. According to the rupture rate values of the numerical simulation, we divided the study area into three classes in the degree of fracture development: A (I > 1.4), B (1.0 < I < 1.4), and C (I < 1.0), thereby performing a quantitative assessment of the developmental degree of the tectonic fractures.

![Fig. 11. Rock strength envelope determined by triaxial compression and deformation tests. (a) First group sample, yielding a rock cohesion C value of 10.20 MPa and an internal friction angle φ of 36.56°; (b) second group sample, yielding a rock cohesion C value of 12.93 MPa and an internal friction angle φ of 36.81°.](image-url)
Fig. 12. Paleotectonic stress field for the lower part of the Es3 unit within the Zhanhua. Depression: (a) maximum principal stress; (b) minimum principal stress; and (c) shear stress. (A) Area around the Yidong 32 well in the north of the study area and (B) area around the Luojia nose-like structure.
7. Results and discussion

7.1. Tectonic stress field

Fig. 12a shows that maximum principal stress values are generally between \(-40 \) and \(-80 \) MPa, indicative of compression. The internal soft zone part of the fault zone has a high degree of rock crushing before the stress is released, meaning that this zone has a low maximum principal stress value. Minimum principal stress values are generally between \(-13 \) and \(-25 \) MPa, also indicative of compression (Fig. 12b). Minimum principal stress values in internal sections of the fault zone are lower than those within the sedimentary units. The distributions of highest maximum and minimum principal stress values are similar to each other, and are generally located between fault zones and are consistent with the trend of these fault zones, indicating that the distribution of tectonic stress was fault-controlled.

Lithologies associated with high stress values are generally calcareous laminated shales and marls that have high carbonate contents; this is clearly evident in Fig. 12b, where high minimum principal stress values are distributed around the Yidong 32 well (A in Fig. 11b) in the north of the study area and the Luoja nose-like structure (B in Fig. 12b). The carbonate contents of the lower section of the Es3 unit in these areas are higher than elsewhere in the study area; however, Fig. 12a shows that the low carbonate blocky mudstone zone around the Yi 171 well in the northeast of the study area is also within a high stress area, primarily due to faulting, indicating that the distribution of stress is controlled by faulting and that lithological changes are merely a secondary factor. Fig. 12c indicates that shear stress values in the study area are generally between \(-9 \) and \(10 \) MPa, and that the shear stress distribution is controlled by the location of fault zones. NE–SW, NNE–SSW, and WNW–ESE striking faults have markedly different influences on shear stress values, indicating that the trend of the fault zone controls the distribution of shear stress.

7.2. Prediction of fracture distribution

Areas of well- and relatively well-developed fractures in the lower part of the Es3 unit were predicted using the results of the modeling outlined above (Fig. 13). Areas with well-developed fractures (\(I > 1.4\)) are widespread, including: (1) NE–SW striking fractures zone within parts of the Luoja nose structure with high carbonate contents, including the location of the L67 and L42 wells; (2) the area near the Yidong boundary fault; (3) the locations of changes in orientation of faults and the zones between faults, including the areas around the Yi 18 and Yi 78 wells; (4) the fault zone near the SG54 and SG4 wells; and (5) the fault tips close to the XYS9 and YD36 wells.

Areas of relatively well-developed fracturing (\(1.0 < I < 1.4\)) are mainly located in the following areas: (1) east of the YD302 and Y1 wells in NE–SW trending zones; (2) around faults adjacent to the L55 and L803 wells in the south of the study area; and (3) around the faults located close to the L45 and L12 wells.

Fracture development was controlled by faulting, and highly fractured areas are located between fault zones, at the intersections of fractures, in areas where fault orientations changes, and at fault tips. In addition, areas of fracture development are distributed along fault zones. Drilling and logging indicate that current shale-hosted oil and gas wells within the lower section of the Es3 unit are all within areas of significant fracture development, indicating a good match between reality and the modeling presented here. For example, the oil and gas wells including L19, L20, L6, L7, L42 are distributed in the areas with well-developed fractures. However, some wells within areas of significant fracture development are unproductive, indicating that although fracturing is the one of the most important factors in terms of hydrocarbon production in the study area, other factors also influence the formation of shale oil and gas reservoirs.

8. Conclusions

(1) Tectonic fractures within a shale reservoir in the lower section of the Es3 unit include both tensional and shear fractures, these fractures are either unfilled or half-filled. The fractures have apertures of 10–100 \(\mu m\), and are generally oriented NE–SW, consistent with the orientation of the present-day stress field. This suggests that NE–SW striking fractures had the highest connectivity and as such were high-priority targets during early
Acknowledgments

The study was supported jointly by the National Natural Science Foundation Project (41372139 and 41072098), the Major Special Project for National Science and Technology (2011ZX05018-001-002 and 2011ZX05009-002-205). We are grateful to the Rock Acoustic Emission Laboratory, Research Institute of Geomechanics, Chinese Academy of Geology, and the Civil Engineering Laboratory of the Civil Engineering College, University of Science and Technology in Beijing, that helped to test and analyze samples.

References


Ding, Y.C., Shao, Z.G., 2001. An experimental research into determination of highest variable GR values. Fractures can also be directly identified, and fracture parameters determined using FMI. (3) Paleotectonic stress field simulations require detailed geological data that can be used to formulate reasonable geological models, and ground stress and rock mechanics data that can provide both mechanical model inputs and boundary conditions. Stress field distributions were determined using DEM modeling, revealing that the lower section of the Es5 unit was affected by stress fields controlled by fault zones, with high-stress zones distributed along faults. Lithological changes controlled stress field distributions in areas without faults, as evidenced by elevated stress fields in lithologies with high carbonate contents. (4) Comprehensive rupture rate analysis was used to quantitatively evaluate fracture development, revealing that tectonic fracturing was closely related to faulting and that fracture development zones are mainly located between fault zones, at the intersections of fractures, in areas where fault orientations change, and at fault tips.


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