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Strain energy density distribution of a tight gas sandstone reservoir in a low-amplitude tectonic zone and its effect on gas well productivity: A 3D FEM study

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ABSTRACT

The tight gas sandstone reservoirs in the Paleozoic of the Sulige gas field in China are highly heterogeneous, and fractures are key factors for stable reservoir production. Low-amplitude folds or nose-like structures are widely developed in the Upper Paleozoic strata in this area. To effectively predict gas well productivity, in this paper, a 3D FEM numerical simulation based on the deformation and energy variation of the rock mass was used to predict the "sweet spots" of gas well productivity in a tight gas sandstone reservoir using the He8 segment of the Middle Permian Xiashihezi Formation in the Central Sulige block as an example. The paleotectonic stress field of the study area during the maximum episode of compression in the Yanshanian movement was restored, and the two rupture parameters of the integrated rupture rate (I_F) and strain energy density (U) were constructed. The strain energy density distribution has a high correlation with gas well productivity, indicating that it can better predict the rock rupture degree in low-amplitude tectonic zones. A complex relationship exists between the strain energy density distribution and low-amplitude folds. The high strain energy density zones are mainly distributed among the high positions and wing areas of the low-amplitude fold zone, but the top area of the low-amplitude fold does not necessarily have a high strain energy density. Portions of the high strain energy density zones are located in the gentle tectonic zone, located near but outside the low-amplitude fold zone. The strain energy in these gentle tectonic zones with a high strain energy density value is relatively high, and the rock mass is prone to rupture. This study is of great value in enriching the prediction of "sweet spots" in tight gas sandstone reservoirs in low-amplitude tectonic zones worldwide.

1. Introduction

The Sulige gas field is located in the northwestern portion of the Yishan slope in the Ordos Basin, China, and is a large-scale inland tight gas sandstone reservoir developed in Paleozoic clastic rocks (Cao., 2012; Lai et al., 2018; Zou et al., 2012). By the end of 2015, the accumulated proven geological reserves of the Sulige gas field exceeded 4×10^{12} m^3 to become the largest natural gas field in China (Lai et al., 2018). The source rocks of this gas reservoir are coal and mudstone of the Upper Carboniferous Benxi Formation and the Lower Permian Taiyuan and Shanxi Formations (Cheng et al., 2016; Zou et al., 2009). The main gas-bearing intervals are the Permian He8 segment of the Xiashihezi Formation and the Shan1 segment of the Shanxi Formation. Previous studies have substantially examined the controlling factors and distribution characteristics of the effective tight sandstone reservoirs by studying the spatial distribution of hydrocarbon source rocks, hydrocarbon generation intensity, reservoir sedimentary microfacies and diagenesis (Cao, 2012; Cheng et al., 2016; Ding et al., 2016a; Farrokhrouz et al., 2014; Gong et al., 2018; Lai et al., 2018; Li et al., 2018; Wessling et al., 2013; Zou et al., 2012, 2014).

Because of the effects of the paleotectonic stress field, many scholars have recently found that natural fractures are highly developed in the tight sandstone reservoirs of the Upper Paleozoic of the Sulige gas field. These fractures include core-scale fractures and microfractures (Lai et al., 2018). Core-scale fractures can be observed with the naked eye, and their fracture lengths are generally less than a meter. Microfractures are usually observed only under the microscope, their length is generally less than 0.05 mm, and their opening degree is generally

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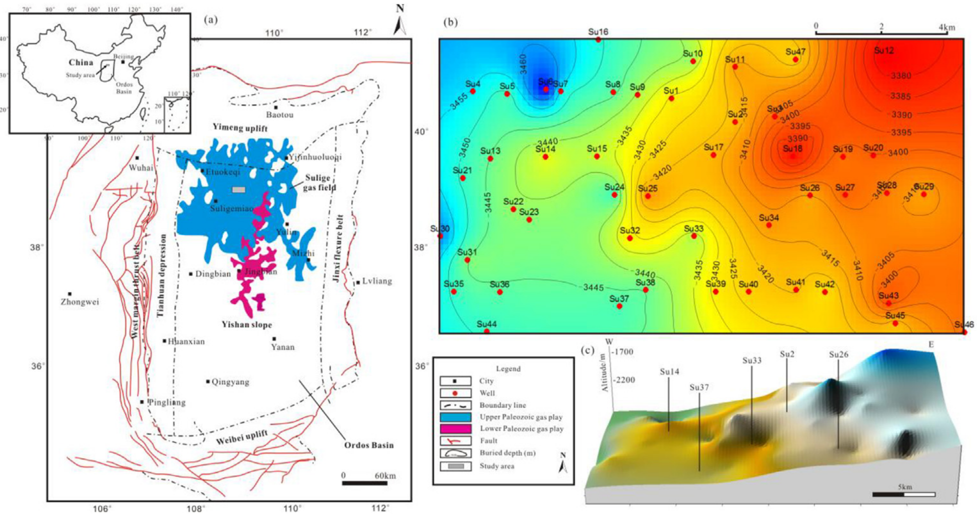

Fig. 1. Location and tectonic features of the study area.
Notes: (a) Location of the Sulige gas field; (b) tectonic features and well of the central Sulige well block; (c) tectonic features of the bottom of the Middle Permian Xiashihezi Formation.

less than 40 μm (Zeng et al., 2010). The core-scale fractures developed in the Upper Paleozoic sandstone of the Sulige gas field are primarily vertical fractures, whereas the microfractures are mainly grain-edge microfractures and grain-penetrating microfractures (Lai et al., 2018; Zou et al., 2012). Hydraulic fracturing in the core-scale fracture or microfracture zone can significantly improve the effect of reservoir development, which is important to increasing the stable production time of the Sulige gas field (Bose et al., 2015; Zhao et al., 2015; Zou et al., 2012). According to previous studies, these fractures were formed in a regional compressive-stress environment during the main episode of the Yanshanian movement, i.e., Late Jurassic-Early Cretaceous (Wan et al., 2010, 2013; Zhao et al., 2016; Zhou et al., 2006).

For the prediction of fractures in tight sandstone reservoirs, certain techniques have been adopted by previous researchers, including geological and log analysis methods, structural curvature analysis methods, seismic prediction methods and FEM (finite element method) (Eltom et al., 2016; English., 2012; Farrell et al., 2014; Hardy et al., 1973; Hooker et al., 2013; Lai et al., 2016, 2017; Laubach, 1997; Lv et al., 2017; Maystrenko et al., 2018; Yin et al., 2016a; Zeng et al., 2012). The geological and log analysis methods are limited by single well data, and their prediction effects have apparent limitations. The structural curvature analysis methods show defects in analyzing the deformation and rupture characteristics of different lithological strata. The resolution of seismic prediction methods generally cannot reach the level of core-scale or smaller fractures. The FEM tectonic stress field simulation is based on the principle of stress and strain transfer, which can produce better predictions of fractures at different scales. However, for different tectonic zones and rock mass types, it is difficult to determine which fracture calculation method is most effective (Eyal et al., 2001; Yin et al., 2017a).

Many theoretical and technical difficulties still exist in predicting small-scale and microscale natural fractures or ruptures worldwide. Microscale ruptures or microfractures have poor development rules in space, and additionally, the scale of such fractures is relatively small, and they are difficult to identify quantitatively (Jamison., 2016; John., 1969; Laubach., 1997; Misra and Gupta., 2014; Price., 1966; Vishal et al., 2013a, 2013b; Yin et al., 2018a, 2018b; Zhao et al., 2016, 2017). For the development of tight gas sandstone reservoirs in the Sulige gas field, researchers are beginning to focus on the microscale ruptures or microfractures because they are important factors in determining whether tight sandstone reservoirs can achieve a stable and long-term production cycle (Jamison, 1983; Lai et al., 2018).

Currently, few studies are available on the quantitative simulation of rock mass rupture in the tight sandstone reservoirs of the He8 segment in the Ordos Basin, which has restricted effective exploration and development of the tight sandstone reservoirs. Previously, researchers focused mainly on the stress environment of the formation of tight sandstone fractures in the He8 segment, including uniaxial stress (horizontal principal stress) evaluation, differential stress evaluation based on basin boundary deformation, tectonic trace stress inversion and layer erosion thickness recovery, etc. (Lai et al., 2018; Wan., 1993; Zhang et al., 2006). In this paper, 3D FEM was used to simulate the rupture parameters of the rock mass using the He8 segment of the Middle Permian Xiashihezi Formation in the Central Sulige well block as an example. The paleotectonic stress field of the study area for the maximum episode of compression during the Yanshanian movement was restored, and, the two rupture parameters of the integrated rupture rate (I_F) and strain energy density (U) were constructed (Hardy et al., 1973; Ju et al., 2014; Ju and Sun., 2016). These parameters represent the probability of ruptures inside the rock mass. The reliability of different numerical simulation methods was verified by comparing their results with the gas well productivity.

2. Geological background

The Ordos Basin is a composite basin located at the junction of multiple blocks (Cao, 2012), and its internal structural units were divided into the Yimeng uplift, west margin thrust belt, Tianhuan depression, Yishan slope, Jinxi flexure belt and Weibei uplift (Fig. 1a). The study area is the central Sulige well block, which is located in the central portion of the Sulige gas field, Ordos Basin (Fig. 1). The structure of the study area is shown in Fig. 1b–c. Low-amplitude structures are developed, and no faults appear in this area. The fold activities were mainly affected by the Yanshanian tectonic movement and were finally shaped during the Himalayan tectonic movement (Cao, 2012). The low-amplitude folds are characterized by broad, gentle folds and nose-like structures (Wu., 2017).

The Upper Paleozoic Carboniferous-Permian strata are the key exploration layers in the study area. Previous studies have made full use of marker layer control, lithofacies tracing, sedimentary cycles and lithologic assemblage to divide the Upper Paleozoic stratigraphic units (Fig. 2) (Cao, 2012; Cheng et al., 2016; Wu, 2017). Multiple sets of gas-bearing layers are developed in the Upper Paleozoic tight sandstone in this area. Among these layers, the Shan1 segment in the Lower Permian Shanxi Formation and the He8 segment in the Middle Permian Xiashihezi Formation are the gas-bearing strata with the highest potential,