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Full Length Article

Modeling fracture connectivity in naturally fractured reservoirs: A case study in the Yanchang Formation, Ordos Basin, China

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ABSTRACT

This paper presents a method to model the connectivity between fractures in naturally fractured reservoirs. A three-dimensional discrete fracture network (DFN) model is generated and validated for a shale gas reservoir using field outcrop data collected from the Upper Triassic Yanchang Formation in the Ordos Basin, China. Based on the DFN model, connectivity parameters including the number of intersections per unit volume and the intersection length per unit volume are calculated. The results suggest that the mean fracture intersection length is 0.54 m. The number of intersections per unit volume and the intersection length per unit volume are 16 intersections/m^3 and 8.58 m/m^3, respectively. The self-intersection behavior and direction vector of the intersections are studied. The simulations show that the intersections between fracture sets 1 and 2 play a dominant role in the fracture intersections of the study area.

1. Introduction

As an important type of unconventional gas resources, shale gas is widely distributed in the Meso-Cenozoic reservoirs of the Ordos Basin in northern China and the lower Paleozoic reservoirs of the Sichuan basin in southern China [1–3]. Due to the low to ultralow permeability of shale matrixes, shale reservoirs need to be fractured hydraulically to produce at an economic rate [4–6]. The permeability of gas shale and the growth patterns of hydraulic fractures in formations are highly controlled by natural fractures [7–9]. Moreover, natural fractures play a critical role on the propagation of hydraulic fractures and the productivity of shale gas reservoirs [10].

In general, natural fractures will connect with each other and the shale matrix to control the flow properties of shale formations. The flow properties of naturally fractured reservoirs are dominated by flow through the fractures. To model the realistic fracture geometry explicitly, the discrete fracture network (DFN) model is developed [11,12]. DFN models are characterized by fracture properties such as length, orientation, intensity, and transmissivity [13]. Connectivity of a fracture network is an important parameter for assessing the flow behavior [14], which can be represented by the geometrical parameters of fractures such as the average number of intersections per fracture (λ), the number of intersections per unit volume (C_1) and the intersection length per unit volume (L_1) according to previous research [15–20]. Connectivity analysis is a crucial procedure to search flow paths, and could be useful for the guidance for the exploration and development of shale gas. Therefore, further research on the effect of fracture geometry on connectivity is necessary.

The Ordos Basin which covers an area of 3.2×10^5 km^2 is one of the largest petroliferous basins in China [21]. It is a typical continental basin that developed on the Mesozoic Cratonic basement. Petroleum resources are found to be mainly distributed in fluvio-lacustrine deposits of the Upper Triassic Yanchang Formation [22]. The Yanchang oil layers are typical tight oil reservoirs characterized by low porosity, ultra-low permeability and strong heterogeneity. The distribution of reservoir properties significantly influences the commercial production of oil and gas [23,24]. Several studies have been undertaken to analyze the characterization of sedimentology by interpreting subsurface data from boreholes in the Yanchang Formation; however, few have investigated the detailed outcrop-based characteristics of this succession [22,25].

The aim of this study is to characterize the geometrical properties of natural fractures in the Upper Triassic Yanchang Formation in the Ordos Basin, China. To achieve this goal, a method to generate a three-dimensional (3-*D*) DFN model through two-dimensional fracture data mapped from field surveys is studied; based on the DFN model, programs for calculating the connectivity parameters of natural fractures are also developed. The results could serve as a guide for the exploration and development of shale gas in the Ordos Basin, China.

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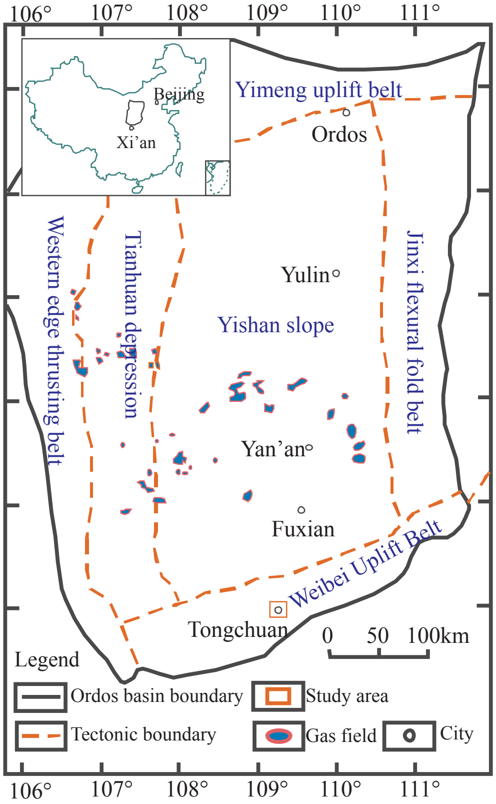

Fig. 1. Tectonic map of the Ordos Basin.

2. Study area

2.1. Geological settings

The study area is located at Tongchuan city, north of the Ordos basin (Fig. 1). The Ordos Basin is a large intracontinental basin bounded by orogenic belts on all margins, situated in the central part of the North China Plate (Fig. 1). Tectonically, the basin can be divided into six structural units: the Yimeng uplift, the Weibei uplift, the Western edge thrusting belt, the Tianhuan depression, the Yishan slope and the Jinxi flexural fold belt [26,27]. The study area is a part of the Weibei uplift region tectonically. The faults exposed in this area mainly trend NE-SW and E-W.

The Triassic Yanchang Formation was deposited in a lake environment and it can be divided into 10 members named Chang 1 (top) to Chang 10 (bottom) [28]. The black mudstones and oil shales in the Chang 7 oil layers are considered to be the most important hydrocarbon source rocks in the Ordos Basin [25]. The Chang 7 shale strata are about 60 m thick on average and are buried at a depth ranging from 1000 to 1650 m. According to sedimentation cycles, the Chang 7 member can be subdivided into three sub-members: the Chang 7-1 sub-member, the Chang 7-2 sub-member and the Chang 7-3 sub-member [29]. The Chang 7-2 sub-member has high content of organic lamina and is targeted as preferable reservoir for shale gas exploitation [30]. In this research, the Chang 7-2 sub-member is selected as the study object. The Chang 7-2 sub-member exposed at this location is 10–25 m thick, with an average thickness of approximately 20 m [22,29]. It consists of primarily black shale and dark mudstone, interbedded with thin layers of dark gray fine-grained sandstone and brown tuff [31]. The content of quartz in the Chang 7-2 black shale varies from 15% to 30%, and the illite-smectite mixed layers vary from 30% to 70% [32]. The kerogen in the shale mainly contains Type II organic matter, and the TOC ranges from 2% to 6% [29,33]. The black shale is characterized by breaks along thin laminae less than one centimeter in thickness [28], called fissility. Dark mudstones, on the other hand, are similar in composition but do not show the fissility.

2.2. Fracture data collection

A total of 118 fractures are obtained using the Brunton compass and rulers from outcrops in the Tongchun City (Fig. 2). The fractures are grouped into two sets (S_1 and S_2) based on their orientations using the modified *K*-means algorithm [34], as shown in Table 1 and Fig. 3. Fracture trace length and fracture spacing are two important geometrical parameters for characterizing fractures. Fracture traces are the intersection of fractures with an observation surface such as a natural outcrop, a pavement or a tunnel wall [35], as shown in Fig. 2. Fracture spacing refers to the distance between two adjacent fractures which belong to the same fracture set (Fig. 2). The average fracture trace length for S_1 and S_2 are 0.87 m and 1.53 m, respectively. Moreover, the average fracture spacing for S_1 and S_2 are 0.44 m and 0.25 m, respectively.

3. Fracture network modelling

The following procedures are carried out to build a three-dimensional (3-*D*) fracture network model using two-dimensional (2-*D*) fracture outcrop data. Fig.4 presents a flow chart for the 3-*D* fracture network modelling.

3.1. Determination of the trace length distribution

Fig. 5 shows a frequency histogram for facture traces measured from outcrops. Six probability distributions, including the triangular distribution, exponential distribution, uniform distribution, lognormal distribution, Poisson distribution and gamma distribution, are selected to find a suitable trace length distribution for each fracture set. Kolmogorov-Smirnov (KS) goodness-of-fit test (Fig. 5) shows that the trace lengths of fracture sets 1 and 2 follow an exponential distribution and a lognormal distribution, respectively.

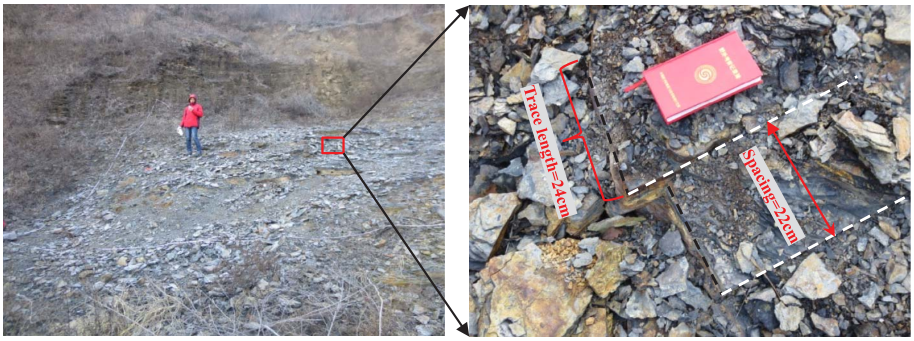

Fig. 2. (a) Outcrop exposed in the Hejiafang village, and (b) two sets of steeply dipping fractures.