Journal of Structural Geology 98 (2017) 53–66

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Experimental and numerical study of hydraulic fracture geometry in shale formations with complex geologic conditions

Xinfang Ma, Tong Zhou*, Yushi Zou

China University of Petroleum, Beijing, 18 Fuxue Road, Changping, Beijing, China

A R T I C L E   I N F O

Article history:
Received 19 October 2016
Received in revised form
31 January 2017
Accepted 9 February 2017
Available online 16 February 2017

Keywords:
Shale
Hydraulic fracture
Bedding plane
Dipping angle
Geometry

A B S T R A C T

Strike-slip fault geostress and dipping laminated structures in Lujiaping shale formation typically result in difficultly predicting hydraulic fracture (HF) geometries. In this study, a novel 3D fracture propagation model based on discrete element method (DEM) is established. A series of simulations is performed to illustrate the influence of vertical stress difference ($\triangle\sigma_v = \sigma_v - \sigma_h$), fluid viscosity, and injection rate, on HF growth geometry in the dipping layered formation. Results reveal that the fracturing fluid can easily infiltrate the dipping bedding plane (BP) interfaces with low net pressure for $\triangle\sigma_v = 1$ MPa. HF height growth is also restricted. With increased $\triangle\sigma_v$, fracture propagation in the vertical direction is enhanced, and a fracture network is formed by VF and partially opened dipping BPs. However, it is likely to create simple VF for $\triangle\sigma_v = 20$ MPa. Appropriately increasing fracturing fluid viscosity and injection rate is conductive to weakening the containment effect of BPs on HF growth by increasing the fluid net pressure. However, no indication is found on whether a higher fracturing fluid viscosity is better. Higher viscosity can reduce the activation of BPs, so a stimulated reservoir volume is not necessarily increased. All these results can serve as theoretical guidance for the optimization of fracturing treatments in Lujiaping shale formation.

1. Introduction

Multistage and multicluster fracturing of horizontal wells is an essential technology to exploit ultra-low permeability shale gas. Large amounts of naturally developed fractures and low horizontal stress difference are important geological preconditions for hydraulic fracturing to form the complex fracture network (Xu et al., 2010; Meyer and Bazan, 2011). Investigating fracture network propagation in such cases is crucial for hydraulic fracturing design and production evaluation.

In recent years, many complex fracture propagation models were proposed to investigate shale fracture network propagation. Xu et al. (2010) proposed a wire-mesh model for practical engineering design. The model assumes fracture propagation geometry is orthogonal fracture networks. Olson (2008) presented a multifracture propagation model based on boundary element method (BEM). This model aims to analyze the mechanical interaction among pressurized fractures without considering fluid flow in hydraulic fractures. Wu and Olson (2015) extended Olson's model to simulate multifracture propagation by considering fluid flow in the wellbore and hydraulic fractures. Meanwhile, Weng et al. (2011) and Kresse et al. (2013) developed an unconventional fracture model (UFM) to simulate fracture growth in naturally fractured reservoirs, and results in the model were corrected by microseismic monitoring. The stress shadow in UFM was explicitly solved by BEM. Yamamoto et al. (2004) and Li et al. (2013) described three-dimensional (3D) fracture propagation models for stimulating multiple fractures by using the finite element method (FEM) and displacement discontinuity method. Apart from BEM and FEM model, Dahi-Taleghani and Olson (2009, 2014) and Keshavarzi et al. (2012) used the extended FEM (XFEM) to analyze hydraulic fracture interaction with natural fractures. The solid deformation in these models is based on the two-dimensional plane strain elasticity theory. The abovementioned BEM and XFEM can efficiently treat the fractures of arbitrary pathways without re-meshing and solve the large amount of computation of FEM (Bittencourt and Wawrzynek, 1996; Martha, 1999). DEM can effectively deal with the dense pre-existing discontinuities or contacts. Many significant studies have also been conducted using the discrete element method (DEM) (Nagel et al., 2013; Nasehi and Mortazavi, 2013;

* Corresponding author.
E-mail address: zhout1986@126.com (T. Zhou).

http://dx.doi.org/10.1016/j.jsg.2017.02.004
0191-8141/© 2017 Published by Elsevier Ltd.

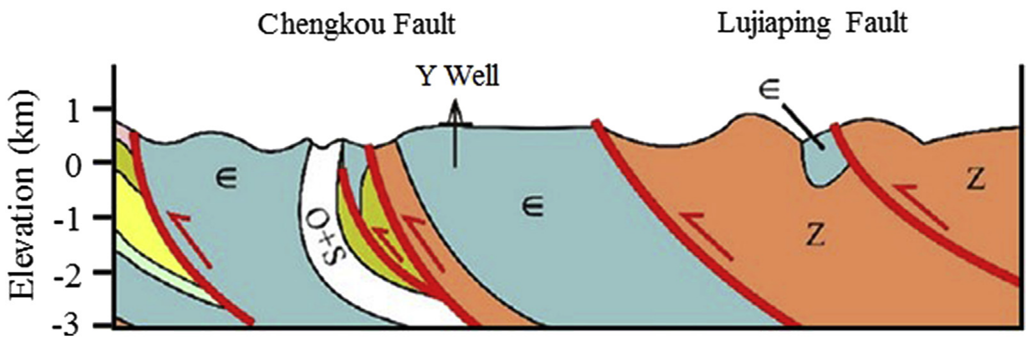

Fig. 1. Regional geological map of Well Y (**modified from** Ma et al., 2015.).

Table 1
Mineralogy analysis of Lujiaping shale formation.

Label	Relative abundance, %					Clay	Quartz	Feldspar	Calcite	Dolomite	Other
	Smectite	Illite	I/S	Chlorite	Kaolinite						
LJP	5.1	13.6	66.7	12.2	2.4	21.3	47.5	6.5	13.3	6.1	5.3

Hamidi and Mortazavi, 2014). However, fracture propagation paths can only be generated in original joint interfaces in these models.

As many bedding planes (BPs) or layer interfaces exist in shale formations, shale formations exhibit multilayered and typically anisotropic properties (Zou et al., 2016a). However, all the models assume isotropic horizontal formations, which may not be true for some shale formations (Heng et al., 2014). Many laboratory-based fracturing tests were conducted to investigate the effects of BPs on the hydraulic fracture network (HFN) geometry (Guo et al., 2014; Zou et al., 2016a). Penetration, diversion, offset, and termination may occur when a hydraulic fracture intersects with a BP (Thiercelin et al., 1987; Zou et al., 2016b,c). HFs propagating along the BP interfaces dominate HF geometry when the difference between the vertical stress σ_v and minimum horizontal principal stress σ_h is less than 6 MPa (Zou et al., 2016a). Layer interfaces, particular weak BPs, may impede HF height growth (Fisher and Warpinski, 2011, 2012; Rutledge et al., 2014).

Previous studies primarily focus on multifracture propagation simulation in the in-situ stress mechanism of normal faults and horizontal formation (Weng et al., 2011; Zhang et al., 2014). However, China's shale gas reservoirs exhibit strong tectonic stresses and complex geological structures (Jia et al., 2012), which cannot be simulated by existing models. For example, the Lujiaping shale formation (Sichuan Basin) is characterized by complex stratigraphic structures, significantly changing dips and dip angles. Compared with horizontal reservoirs, several representative HF geometries after fracturing treatment: (1) HF tends to propagate crossing the BPs without changing the pathway, generating a simple horizontal or vertical fracture; (2) Fluid can easily infiltrate the BP interface and a single inclination HF growth along the BP interface near the wellbore; (3) A complex HFN interweaves by horizontal fracture and BPs or are interweaved by VF and BPs. Li et al. (2016b) found that HFs tend to propagate more along BP and fracture height evolution is more confined with increased BP dipping angle, but the model is 2D. Understanding HF geometries in such complex geologic conditions as mentioned are crucial in formulating the best stimulation strategy. So far, few studies have focused on the effects of dipping multilayered and formation anisotropic properties. Therefore, shale BPs and anisotropic characteristics must be considered to simulate complex HF propagation.

In the present work, a 3D fracture propagation model based on DEM is established. Transverse isotropy constitutive relations are primarily considered to characterize layered shales in the high dip angle formation. Thereafter, a series of sensitivity analysis were performed to investigate some controlling factors of complex fracture geometry, such as in-situ stress, fluid viscosity, and injection rate. To validate our model, laboratory experiments were conducted with the 40 cm cubic shale samples in a ture-triaxial hydraulic fracturing system. This study investigates the complex HF geometry under complex geologic conditions, thereby, providing technical guidance for the optimization of fracturing treatments in Lujiaping shale gas reservoirs.

2. Geological background

The Lujiaping shale formation in Sichuan Basin, Southwest China, is 1400 m deep and is characterized by complex stratigraphic structures, significantly changing dips and dip angles, as shown in

Fig. 2. Outcrops of Lujiaping shale formation.