



# Research Advance on the Diagnosis Technology of Hydraulic Fractures in Shale Reservoirs

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## INTRODUCTION

With the growth of the world economy, the demand for oil and gas is also rising, and conventional oil and gas resources have been unable to meet the huge energy demand (Tong et al., 2018; Akadiri et al., 2019; Feng et al., 2020; Li et al., 2020; Lin and Agyeman, 2021). Shale oil and gas resources are widely distributed and abundant, which will become an important area for strategic replacement and development. Since the successful development of shale gas reservoirs in North America, hydraulic fracturing has become a key technology for the development of unconventional oil and gas reservoirs (Cipolla et al., 2008; Yao et al., 2012; Xu et al., 2013). The reservoir stimulated technology represented by volume fracturing, to produce a complex fracture network and clarifying the morphology of the complex fracture network, is an important prerequisite for the evaluation of the fracturing effect (Sheng et al., 2019; Zhao et al., 2021). However, shale reservoirs have complex mineral composition, natural fractures, and bedding structures. The existing fracture diagnosis technology is not mature enough, and there are problems of low efficiency and poor simulation accuracy, which cannot accurately match the actual fracture network morphology (Huang et al., 2021). Fracture diagnostic technology is the main approach to determine fracture network morphology. The purpose of conventional hydraulic fracturing is not to form complex hydraulic fractures or fracture networks. These methods are mainly suitable for conventional bi-wing fracture types and have great limitations for the diagnosis of complex fracture networks (Yao, 2018). Therefore, this article discussed the current research progress of the fracture diagnosis technology, analysis shortcomings of different methods, and provides suggestions for further research.

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## FRACTURE DIAGNOSIS TECHNOLOGY

The induced fractures produced by hydraulic fracturing are complex, and the morphology of the fracture network plays a key role in productivity. There are four main kinds of the fracture diagnosis technology, namely, the fracturing data analysis method, production data analysis method, near-wellbore measurement method, and far-wellbore measurement method (Nolte, 1979; Romero et al., 2000; Qu et al., 2013).

## Fracturing Data Analysis Method

Fracturing data analysis is the most economical method. However, the accuracy of this method is also not high. This method mainly includes the double logarithmic curve diagnosis method, net pressure fitting method, pressure fluctuation evaluation method, and G function method (Nolte, 1979; Molenaar et al., 2012).

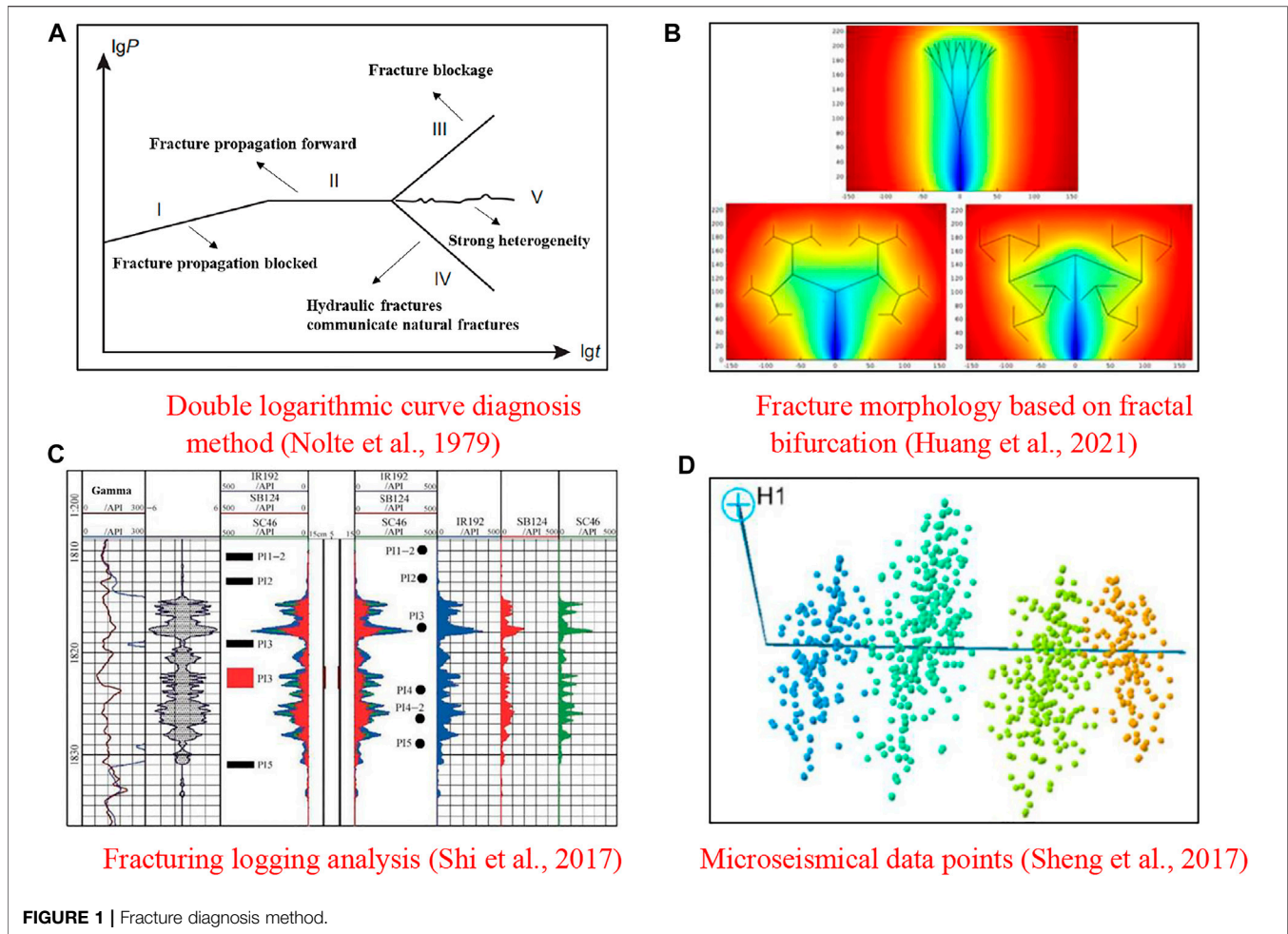


FIGURE 1 | Fracture diagnosis method.

- Double logarithmic curve diagnosis method: the variation of bottom pressure with time during hydraulic fracturing reflects the propagation of fractures (Nolte, 1979; Meyer and Bazan, 2011; Molenaar et al., 2012). Nolte (1979) first proposed the double logarithmic curve diagnosis technology for fracture diagnosis, as shown in **Figure 1A**. By analyzing the curve of logarithmic bottom hole pressure ( $lgP$ ) with logarithmic time ( $lgt$ ), the fracture propagation morphology is judged. Minner et al. (1996) improved the accuracy of the method and provided the basis for fracturing and evaluation.
- Net pressure fitting method: Since the 1990s, scholars began to study how to analyze the fracture parameters by fitting the actual net pressure and the net pressure calculated by the mathematical model so as to improve the success rate of hydraulic fracturing (Minner et al., 1996; Romero et al., 2000). Yang (2021) proposed the net pressure fitting method, changing the fracture parameters to fit the net pressure. In the process of net pressure fitting, the net pressure calculated from the wellhead is considered as actual net pressure. The error between the calculated net pressure and the actual net pressure is reduced by adjusting the fracture parameters. The fracture morphology calculated by the net pressure fitting method has a high fitting rate with the actual fracturing data.
- Pressure fluctuation evaluation method: Bian et al. (2016) proposed a pressure fluctuation evaluation method based on fracturing data. This method divides the fracturing operation curve into the ahead fluid injection stage and fracture propagation stage. The brittleness and plasticity of the reservoir can be qualitatively judged by counting the number of reservoir ruptures, the average pressure drop, and the average pressure drop rate during the ahead fluid injection stage (Eshkalak et al., 2014). The study showed that the frequency and amplitude of pressure fluctuation in the fracturing stage reflect the complexity of the fracture network, and the fracture morphology of the far well can be comprehensively diagnosed combined with the brittleness and plasticity of the reservoir.
- G function method: the pressure drop equation is established by establishing the relationship between the pressure drop after the pump stop and the G function. Subsequently, the closure of hydraulic fractures is identified, and the fracture parameters are calculated (Nolte, 1979). The G function method based on the pressure drop curve needs the pressure test data after a long time of pump shutdown. If the time of reservoir monitoring

pressure is short, it cannot be used to describe hydraulic fractures (Soliman et al., 2010; Wu et al., 2011; Yao, 2018).

## Production Data Analysis Method

The production data analysis method mainly includes an analytical/semi-analytical model and a numerical simulation model (Stalgorova and Mattar, 2012; Huang et al., 2021).

- **Analytical/semi-analytical model:** The analytical/semi-analytical model of hydraulic fracturing is a necessary means for dynamic analysis (Chen et al., 2019). Combined with the actual unstable pressure response, the fracture parameters such as the fracture length, fracture flow capacity, and fracture width are inverted (Tian et al., 2017). Chen et al. (2019) proposed a dynamic inversion method for comprehensive analysis of microseismic data, production data, and well test data, which further reduced the multiplicity of inversion results of fracture parameters.
- **Numerical simulation model:** Based on microseismic data and production data, Mayerhofer et al. (2010) evaluated fracture network morphology, fracture spacing, and fracture total length by the historical fitting method. Based on the fracture propagation model and production data, Cipolla et al. (2011) established a fracture parameter inversion method considering microseismic data and production data. However, most of the aforementioned work is based on the assumption of single fractures or orthogonal fractures, without considering the actual fracture network morphology, as shown in **Figure 1B**.

## Near-Wellbore Measurement Method

Near-wellbore measurement methods often use radiotracers to monitor wellbore data (Guo et al., 2019; Liu et al., 2018; Jin et al., 2021; Liu et al., 2020a). Different radioactive materials were put into the fracturing fluids, gamma spectrum was measured by using a logging instrument, the distribution of the proppant was obtained, and then the fracture height and width were calculated (Gulrajani and Romero, 1996; Shi et al., 2017; Liu et al., 2020b), as shown in **Figure 1C**. Near-wellbore measurement technology is limited by a small monitoring range, resulting in low accuracy of evaluation results. This method is suitable for small fracture ranges or for rough analysis.

## Far-Wellbore Measurement Method

The far-wellbore measurement methods mainly include the microseismic monitoring technology, inclinometer fracture monitoring technology, and potentiometric fracture monitoring technology (Albright and Pearson, 1982).

- **Microseismic monitoring technology:** microseismic monitoring technology is based on acoustic emission and seismology. It draws spatial images of fractures by observing tiny seismic points generated during hydraulic fracturing and monitors the propagation of hydraulic fractures (McMechan et al., 1985; Warpinski et al., 2009; Sheng et al., 2017), as shown in **Figure 1D**. By analyzing the microseismic monitoring results, we can not only analyze the fracture propagation along various directions but also analyze the fracture trend of each section and judge the maximum horizontal stress direction of the reservoir.

- **Inclinometer fracture monitoring technology:** two sets of inclinometers are arranged at the wellhead and downhole in adjacent wells to monitor the reservoir inclination data caused by fracture propagation during hydraulic fracturing. Combined with the inclinometer data, the fracturing parameters are determined by geophysical inversion calculation (Shi and Lin, 2021).
- **Potentiometric fracture monitoring technology:** potentiometric fracture monitoring technology is also an effective method widely used to monitor hydraulic fractures (Shi and Lin, 2021). The technology is based on the theory of electrical exploration, by monitoring the changes in the ground electric field caused by the fracturing fluid injected into the reservoir with high ionization energy, to explain the parameters of fracture morphology, length, and orientation.

## COMPARISON AND ANALYSIS

Compared with different fracture diagnosis methods, the traditional fracturing data analysis methods and production data analysis methods are more economical. However, most of these methods are based on single or orthogonal fracture assumption, without considering the actual complex fracture network morphology. The near-wellbore measurement method and far-wellbore measurement method are mostly based on field experiments, which are difficult in technology and high in cost, and are not conducive to popularization and application.

In the aforementioned method, the net pressure fitting method can be combined with the fracture propagation model, and the fracture morphology is constrained by the pump pressure and injection rate. This method is closely related to the reservoirs. However, the net pressure fitting method still has some problems to be solved. 1) A fast and efficient fracture propagation simulation method with certain randomness is needed. 2) A fast and efficient calculation method and a fitting method of net pressure for complex fractures are needed. The time of hydraulic fracturing is short, and there are many influencing factors. It is important to determine the practicability of this method to realize net pressure fitting by appropriate methods.

## CONCLUSION AND SUGGESTION

- 1) The fracturing data analysis method and production data analysis method cannot describe the fracture morphology. Near-wellbore measurement method and far-wellbore measurement method are difficult to be popularized. The net pressure fitting method can make good use of fracturing data, combined with the fracture propagation model, and can significantly improve the accuracy.
- 2) At present, there are still some urgent problems to be solved in the net pressure fitting method, that is, it needs a fast and efficient fracture propagation simulation technology with certain randomness, a fast and efficient calculation method, and the net pressure fitting method of complex fractures.

## AUTHOR CONTRIBUTIONS

YC was responsible for the overall research and writing work, TZ was responsible for the main idea of the article, and other authors were responsible for writing and layout.

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