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A new method for evaluation of fracture network formation capacity of rock

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HIGHLIGHTS

- A new method for evaluation of fracture network formation capacity is developed.
- Acoustic emission location is used for dynamic monitoring of SCA fracturing.
- Three commonly used brittleness evaluation methods are analysed.
- Fracture is characterized by using fractal dimension of the trace and areal density.

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ABSTRACT

An effective evaluation on fracture network forming capacity is key to the whole process of shale gas exploration. At present, neither a clear standard nor a generally accepted evaluation method exist. In this study, a novel "Soundless Cracking Agent (SCA) fracturing evaluation method" was developed. The fractures were characterized quantitatively using fractal dimension of the trace on the core surface and areal density. Acoustic emission (AE) location was used for dynamic monitoring and analysis. The results show that the fractal dimension can be used for quantitative evaluation of complexity of fracture network. The higher the rock hardness, the smaller the fracture density after fracturing is; the higher the brittleness, the larger the fracture density after fracturing is. The development degree of natural fracture systems and sedimentary bedding is a key factor to control the propagating morphology of fractures. The number of AE events for sandstones with low clay content (<25%) is huge, and there are obvious take-off spots for cumulative curves and frequency distribution curves. The AE events for sandstones are distributed along the main fractures, with simple planar fractures clearly present after fracturing. But for shale, the number of AE events is less, with no obvious take-off spots, and AE events are scatteredly distributed. The higher the clay content and the lower the quartz content, the smaller the number of AE events is, and the smaller the frequency and the sound source amplitude are. For sandstone, the number of AE events decreased by about 75% due to the increase of clay content by 20%. The new method enables a comprehensive reflection of the characteristics of rock hardness, brittleness and natural fractures system. This work is valuable for the evaluation of hydraulic fracturing effects in unconventional oil and gas reservoirs in the future.

1. Introduction

Shale gas refers in particular to an unconventional natural gas hosted in shale reservoir. It is mainly located in the dark mud shale or high carbon mud shale, and exists in either adsorbed or free state [1–3]. Shale gas reservoirs generally show physical properties of low porosity and low permeability. The gas flow resistance of shale is much greater than that of conventional natural gas, resulting in greater exploitation difficulty and lower recovery efficiency. Economic development of shale gas requires the use of horizontal wells and hydraulic fracturing stimulations. Under the action of lowering pressure by drilling well and completion well, the shale gas in a fracture system flows to the wellbore, while shale gas in the matrix system desorbs from the matrix surface. Under the action of concentration difference, shale gas diffuses from the matrix system to the fracture system. Under the action of flow potential, shale gas flows to the wellbore through the fracture system. About 90% of U.S. Devonian shale gas wells need hydraulic

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fracturing to increase the space and connectivity of fractures, so that more adsorbed gas desorbs and gathers towards the fractures. Therefore, the greater the fracture volume, the greater the shale gas production will be.

Hydraulic fracturing based on stimulated reservoir volume is the first-choice technique to achieve commercial development of shale reservoirs [1–3]. During fracturing, the natural fractures reopen, and shear sliding develops in brittle rocks, forming a network of fractures (artificial ones and natural ones) interconnected with each other. This technology can enlarge the stimulated reservoir volume, thus increasing the total production and the ultimate recovery. The assessment on the ability of fracture network forming using hydraulic fracturing is crucial and a premise of the evaluation of the development value of shale reservoirs. The key factors affecting the morphology of post-fracturing network include horizontal in-situ stress difference, rock brittleness and natural fracture system (sedimentary bedding) [4–9]. In addition, the morphology of fracture network can also be affected by fracturing operation parameters (volume of fracturing fluid, flow rate, spacing between fracturing segments [10,11]) and fracturing techniques (horizontal well multistage fracturing, synchronous fracturing, zipper fracturing and refracturing [12]).

The horizontal stress difference of the formation can be obtained from laboratory test or field monitoring. There are many methods to evaluate the rock brittleness [5,9,13], and most require the performance of different rock mechanics experiments, with results generally divergent. In addition, the brittleness of the rock is the essential but not sufficient to generate complex fracture network. It should be noted that natural fracture system and depositional beddings are also among the key factors. However, since the observation and evaluation of a natural fracture system is rather difficult and complicated, and the fracture propagation mechanism of the shale reservoirs remains unclear, it is extremely difficult to solely evaluate the effect of natural fracture system. Laboratory physical simulation using a large-size tri-axial system [14] requires the presence of the large-size outcrops and complex experiment procedures, and is not applicable for field test. Therefore, the fracability evaluation considering both rock brittleness and fracture system for evaluating fracture network formation capacity using hydraulic fracturing in shale reservoirs is urgently required, and proposed in this study.

Full-diameter cores drilled from the shale gas reservoir or outcrops were used as the test objects. Soundless Cracking Agent (SCA) was used to generate fractures without considering the horizontal stress difference. SCA is a kind of grey powder, consisting of calcium oxides, silicon dioxide, ferric oxide and some other ingredients. When the SCA is mixed with an appropriate amount of water and poured into the pre-drilled holes, it will start to expand after an hour, with an expansion ratio increasing with time extended. The fractal dimension value of the fracture surfaces and surface density were used to quantify the fracture geometry, and the number and the size of caved rock fragments were evaluated. According to the obtained results, the fracability of shale reservoirs could be determined. The proposed method has the advantages of visibility, reliability, simplicity and effectiveness.

In order to more accurately describe the real 3D fracture morphology and verify the reliability of the proposed method, an indoor AE location [15–17] experiment was carried out for dynamic monitoring and analysis. The purpose was to further understand and explore the microseismic monitoring of hydraulic fracturing for shale reservoirs and different fracture propagating rules for sandstones and shales.

AE location is an important means to study internal deformation and failure mechanisms of rocks. Generally, the fracture propagation in brittle rocks is accompanied by instant energy release, while elastic stress wave is produced as the source of AE energy. Since AE signal is the strain energy released by fracture propagation in the interior of rock, each AE signal contains abundant information about the changes of rock's internal structure. Currently, a number of experiments of AE location have been carried out to study the process of fracture propagation of granite or sandstone under uniaxial or triaxial compression conditions [18–23], but those of AE monitoring and analysis in the process of fracturing with SCA have not yet been reported for shale and sandstone.

Using 10 types of cores in this study, the rock mechanics parameters were tested, and the three commonly used shale brittle evaluation methods were employed to calculate the brittleness of rocks. On this basis, the experiments for evaluating the ability of fracture network formation by fracturing using the new method were conducted. In addition, for shale (drilled along a direction parallel or perpendicular to the bedding plane) and sandstone [24], the AE location experiments were also performed in the process of fracturing with SCA. The results of the study are a guidance for the shale reservoir evaluation and development in the future.

2. Method for rock brittleness evaluation

As a key factor affecting the morphology of post-fracturing network in shale reservoir, the plastic–brittle property has always been the focus of research. Sondergeld et al. [5] developed a mineralogical method to determine the rock brittleness index. However, Matthews et al. [6] contended that carbonate was more brittle compared with clay and quartz and should belong to brittle mineral, thus no uniform criterions existed for mineralogical method [25]. Rickman et al. [9] illustrated an application of petrophysical properties for optimizing the hydraulic fracturing design and presented the method that used the Young's modulus and Poisson's ratio [26] to compute the rock brittleness index "BRIT". When BRIT > 40, the rock was brittle; when BRIT > 60, the rock was highly brittle. Goktan and Yilmaz [13] introduced a simple method to compute rock brittleness index, "BI", based on the uniaxial compressive strength and tensile strength. When BI > 15, the rock was brittle; when BRIT > 25, the rock was highly brittle. In addition, according to the load–displacement curve in the process of rock crushing, the plastic coefficient could be computed to quantitatively characterize the rock plasticity and brittleness [27]. Plasticity coefficient is the ratio of total work AF to work of elastic deformation AE before the rock crushes. For brittle rocks, the plasticity coefficient K_p is equal to 1, for brittle–plastic rock, $1 < K_p < 6$, for plastic rock, $K_p > 6$. According to the magnitude of the plasticity coefficient, the rock can be divided into three classes and six grades.

In this article, 10 types of rocks including shale A and B were measured. Shale A was drilled along a direction perpendicular to the bedding plane, and the mineral analysis showed that the average contents of quartz, carbonate and clay were 56.5%, 9.7% and 29.3%, respectively. However, the natural fractures and depositional beddings were not well developed. The four cores for shale B have well-developed natural fractures and depositional beddings. The drilling directions include parallel to the beddings (cores 10#a and 10#b) and perpendicular to the beddings (cores 10#c and 10#d), and the mineral analysis showed that the average contents of quartz, carbonate and clay were 41.3%, 13.1% and 39.9%, respectively. According to the experiments, the rock mechanics parameters were obtained and the brittleness evaluations were performed as shown in Table 1.

It can be obtained from Table 1 that all cores are representative with the Young's modulus ranging from 5.1 GPa to 51.2 GPa. Shale A has higher Young's Modulus and accords well with the perspective shale evaluation standard given by Sondergeld et al. [5], which specifies that the Young's modulus should be above 24.0 GPa. However, the Young's modulus of shale B is lower. In addition,