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An improved evaluation method for the brittleness index of shale and its application — A case study from the southern north China basin

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ABSTRACT

The brittleness index (BI) is an important indicator used to characterize the brittleness and fracability of shale reservoirs. The BI calculation methods based on the brittle mineral and mechanical parameters content of shale are widely used, but there are still some limitations, such as the separation of minerals and mechanics, the inconsistent viewpoints regarding brittle minerals of different scholars, and the equivalent treatments of the brittleness of each mineral. By taking the Permian Shanxi and Taiyuan Formation in the Southern North China Basin (SNCB) as an example, this paper improved the BI calculation method, then examined and applied it. The results show that the weight coefficients of brittleness contributions of various minerals are different because of their marked differences in mechanical properties. By multiplying and summing the mineral contents and their weight coefficients, an improved evaluation method for a shale's BI is proposed. The new BI has more reasonable physical significance and avoids the equivalent treatment of various minerals on the rock brittleness. Applications indicate that when compared with the original mineral BI, most of the new BI decrease, which reduces the artificial optimization of the shale brittleness. The new BI of limestone reduces significantly, which reveals that the brittleness and fracability of limestone should be less than those of shale and sandstone. The roof and floor limestone of shale will prevent induced fractures from propagating across the interfaces between the limestone and shale, and can thus be used as an effective barrier bedding to help the fracturing and formation of the complex fractures in shale sections. The improved BI method is able to evaluate shale brittleness and selecting a favorable fracturing shale section more accurately.

1. Introduction

Shale brittleness has a great influence on the degree of difficulty of fracturing, and the formation and shape of induced fractures (Rickman et al., 2008; Holt et al., 2015; Rybacki et al., 2016). The brittleness index (BI, also known as the brittleness ratio, brittleness coefficient, or ductility number) has been widely used to characterize the shale brittleness. The brittleness is an indicator influenced by many factors, such as rock minerals, rock mechanical properties, in-situ stress, confining pressure and strain rate, porosity, fracture, grain size, spatial arrangement and structural configuration of the components, which leads to a number of descriptions and definitions of brittleness. Therefore, there are more than 20 methods to determine the BI (Altindag, 2003; Rickman et al., 2008; Tarasov and Potvin, 2013; Rybacki et al., 2016; Zhang et al., 2016).

The evaluation methods proposed by Rickman et al. (2008), based on the rock's mechanical elastic parameters (Young's modulus and Poisson's ratio) and the brittle mineral content are widely used for their simplicity and practicability. The Young's modulus and Poisson's ratio are the key rock mechanical parameters used to characterize shale brittleness (Rickman et al., 2008; Sone and Zoback, 2013). The greater the Young's modulus is and the lower the Poisson's ratio is for a shale, the stronger its brittleness is and the more favorable it is for the fracturing and the formation of a complex fracture network (Rickman et al., 2008). The mechanical BI can be acquired according to the normalized Young's modulus and Poisson's ratio. It can more authentically reflect the shale brittleness and fracability. However, a rock mechanical experiment requires a large volume of samples and high costs; thus,

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limited mechanical data can be measured. Indeed, the mechanical parameters can be derived from a sonic log, but their accuracy need be further improved because there is sometimes a big difference between the mechanical parameters from the log and those from the tests.

In contrast, the mineral BI has greater practicality. The mineral BI is defined as the ratio of the brittle mineral content to total mineral content. However, the criteria used to identify brittle minerals in previous works are inconsistent. Some scholars argue that quartz is the only brittle mineral (Jarvie et al., 2007; Rickman et al., 2008; Gholami et al., 2016). Some think that the brittle minerals contain quartz, dolomite, and even pyrite (Wang and Gale, 2009; Qin et al., 2016; Zhang et al., 2017), or quartz, feldspar, and dolomite (Nelson, 2001). The quartz and carbonate minerals are treated as brittle minerals (Matthews et al., 2007; Sondergeld et al., 2010; Li, 2013). Some scholars even regard quartz, feldspar, pyrite, and the carbonate minerals (e.g., calcite, dolomite, siderite, etc.) as brittle minerals (Jin et al., 2014a, b; Guo et al., 2015; Zhao et al., 2015), which means that the other minerals, excepting clay, contained in most shales are all brittle. The calculated BI is mostly greater than 40% of the critical value of the shale's favorable reservoir, and is generally larger than that of the mechanical BI. Thus, it artificially optimizes the brittleness and the fracability of the shale. In addition, there are two problems that exist in the BI calculation. First, the judgment of brittle minerals has not taken into consideration the physical properties of the minerals themselves. Second, each mineral is regarded as having equivalent contribution to the shale brittleness once it is identified as a brittle mineral. In fact, each mineral has a different chemical composition and mechanical properties, as well as brittleness. Therefore, treating the contributions of each mineral as equivalent is questionable. In addition, whether the mechanical BI or the mineral BI, the mechanical properties and minerals of a rock are considered separately.

This paper analyzes the mineral composition, mechanical properties and brittleness performance of shale, and clarifies the brittleness differences among various minerals. By considering both the mineral compositions and their mechanical properties, the evaluation method for the shale BI is improved to assess the brittleness and fracability of a shale in a more accurate and objective manner, providing technical support for the favorable fracturing section of shale reservoirs.

2. Geological setting

2.1. Basin setting

The Southern North China Basin (SNCB) is in the southern portion of the North China block (Fig. 1). It is divided into the Kaifeng depression, Taikang uplift, Zhoukou Depression, Bengbu uplift, and Xinyang-Hefei depression from north to south (Xu et al., 2004; Yu et al., 2005). The Permian is a layer of marine-continental transitional facies among which the Taiyuan Formation is largely a barrier-coast facies and Shanxi Formation is mainly a delta (Hu et al., 2012). The rock types consist of limestone, shale, fine siltstone, coal, etc. From 2014 to 2017, a total of four shale gas exploration wells were drilled in the northwestern portion of the SNCB (located in the Taikang uplift) — Mouye-1 (MY1), Zhengxiye-1 (ZXY1), Zhengdongye-2 (ZDY2), and Wencan-1 (WC1). These wells showed good shale gas potential in the same target layers — the Shanxi Formation and Taiyuan Formation.

2.2. Shale characteristics

In this study, a total of 73 core samples (50 from MY1, 23 from ZXY1, 43 from the Shanxi Formation and 30 from the Taiyuan Formation) were tested for various parameters, including total organic carbon (TOC), whole-rock minerals, clay minerals, and uniaxial mechanical experiments (to gain the Young's modulus and Poisson's ratio). In addition, the samples have three types of lithologies: 45 shales, 20 sandstones and 8 limestones, which better reflect the influence of mineral type and contents on rock brittleness and analyze the role of the limestone and sandstone in shale gas.

2.2.1. Mineral composition

The shales of the Permian Shanxi and Taiyuan Formation in the SNCB include ordinary shale, carbonaceous shale and silty shale. They mainly consist of clay minerals, with an average content of more than 47%, which indicates that the brittleness of these shales is weak. The majority of clay minerals are illite, smectite and illite mixed-layer, with an average of 44%–45% and 27.5%–31.5%, respectively. The quartz ranks second with an average content of 38%–40%. Compared with the Shanxi Formation, the shales in the Taiyuan Formation are composed of more carbonate and pyrite. The average contents of pyrite, siderite, dolomite and calcite are 3.9%, 2.8%, 2.2% and 1.2%, respectively (Table 1).

2.2.2. Mechanical properties

In general, the shale with a Young's modulus greater than 30 GPa and a Poisson's ratio less than 0.25 has a good brittleness and a strong fracability (Zou, 2013). The Young's modulus of the Shanxi Formation shales are 9.39–25.14 GPa, with an average of 17.28 GPa, and an average Poisson's ratio of 0.21 with range from 0.18 to 0.28. The Young's modulus and Poisson's ratio in the Taiyuan Formation are 19.90–38.68 GPa and 0.15–0.23, respectively, with average values of 26.10 GPa and 0.20, respectively (Fig. 2). The Taiyuan Formation shales have a better brittleness and a stronger fracability than the Shanxi Formation ones, but these shales as a whole have the weaker brittleness and fracability. This corresponds to the understanding that clay mineral contents in the Taiyuan Formation shales are lower.

3. Improved method for the brittleness index

3.1. Mechanical property of the minerals

The statistics indicate that the possible brittle minerals such as quartz, feldspar, calcite, dolomite, siderite and pyrite have different relationships with the Poisson's ratio (the slope of the fitted line varies) in the study area (Fig. 3). Some researchers also have determined the statistics of the mechanical differences of some minerals (Gholami et al., 2016; Zhang et al., 2017). Therefore, there are obvious differences in the mechanical properties of the various minerals. The mechanical parameters of each mineral listed in the previous literature also fully reflect this point (Table 2). It should be noted that the Young's modulus is transformed from the Poisson's ratio and bulk modulus or shear modulus for the all minerals according to the Eqs (1). and (2) (Schon, 2011). The final Young's modulus is the average of the two numbers. For the clay minerals, the Young's modulus is gained from the Eq. (3), and part of the Poisson's ratio is obtained by Eq. (4) (Schon, 2011).

$$E = 3 \cdot k(1 - 2 \cdot \nu) \tag{1}$$

$$E = 2 \cdot \mu(1 + \nu) \tag{2}$$

$$E = 2 \cdot k\mu/(3 \cdot k + \mu) \tag{3}$$

$$\nu = (3 \cdot k - 2 \cdot \mu)/2(3 \cdot k + \mu) \tag{4}$$

where E is the Young's modulus, GPa; k is the bulk modulus, GPa; ν is the Poisson's ratio, dimensionless; and μ is the shear modulus, GPa.

By taking the average mechanical values as an example (Table 3), pyrite has the largest Young's modulus of 307.1 GPa and a Poisson's ratio of 0.15. The quartz's Young's modulus is also greater than 90 GPa, and the average Poisson's ratio is only 0.07. The Young's modulus of the dolomite and siderite are both greater than 120 GPa, and their Poisson's ratio is 0.26 and 0.32, respectively. The Poisson's ratios of the plagioclase, calcite and clay minerals are greater than 0.3, with a low Young's modulus. The kerogen or organic matter has only a 6.2 GPa Young's