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Perspective

Brittle minerals, mechanical properties and fracability evaluation of shales

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Abstract:
The brittleness of shales is critical to hydraulic fracturing since rock with high brittle minerals are more likely to fracture and maintain open fractures. Shale rocks have a wide range of constituting components, and different minerals display distinct elastic behavior. The microscale measurements of mechanical properties indicate that pyrite has the highest Young's modulus, followed by quartz and feldspar. Organic matter was commonly recognized as the soft component, and has very low Young's modulus. Alkaline minerals show similar Young's modulus values to quartz and feldspar, and can be grouped into brittle minerals. The relative content, source and structure of brittle minerals can affect rock brittleness from multiple scales. Understanding the relationship between mineral compositions and geomechanical properties is beneficial for fracability estimation in engineering applications for shales.

1. Introduction

Shale has a complex rock composition, including a wide range of inorganic and organic components (Jarvie et al., 2007). There are significant differences in the types, contents, and sources of shale brittle minerals in different depositional environments, leading to varying petrophysical properties, especially geomechanical behavior (Dong et al., 2017; Liu et al., 2024). The brittleness and fracability of shales are crucial to obtain high-yield industrial oil and gas production (Cui et al., 2023). It is of great significance to recognize the types and sources of brittle minerals in shales, revealing their geomechanical behaviors, and establishing a fracability evaluation method. The aim of this work is to provide scientific basis for shale oil and gas sweet spot evaluation and efficient development.

2. Brittle minerals in shales

Shale rock composition primarily includes quartz, feldspar, carbonate, clay, pyrite, and organic matter. These minerals have multiple sources, including extrabasinal and intrabasinal sources, as well as authigenic minerals formed during diagenesis. The mixing of different sourced minerals is an important control on shale rock brittleness, which have been reported in many shale formations (Milliken and Olson, 2017). The extrabasinal components primarily include clay minerals, detrital quartz, feldspar, and terrestrial organic materials. The intrabasinal components mainly include calcite, dolomite, pyrite, barite, bioclasts, such as radiolarians and sponge spicules, along with marine organic matter (Zhao et al., 2017; Peng et al., 2020). Clay minerals generally contain kaolinite, smectite, illite, and chlorite, and can be either transported into the basin by detrital flux or generated through diagenetic alterations, for example, the smectite to illite transformation and feldspar

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dissolution. In general, organic matter and clay minerals are regarded as the ductile materials in shales. Quartz is the typical brittle mineral in shales, and it is generally considered to play a positive role in shale brittle behavior (Thyberg et al., 2010; Dong et al., 2017). Both primary and authigenic quartz are present in shales (Dowey and Taylor, 2017). Primary types of quartz include biogenic forms, including radiolarians and sponge spicules, and detrital silt-size grains (Wei et al., 2021). The types of authigenic quartz include quartz overgrowths, pore-filling microcrystalline quartz in intragranular pores, and microcrystalline quartz throughout the clay-size matrix. Calcite in shales can be existed as blocky calcite, calcite skeletal debris and authigenic calcite that was frequently cemented in intergranular pore spaces (Milliken et al., 2013).

Recent studies suggest that both petrophysical and geomechanical properties of shale reservoirs are influenced by original rock composition, fabric, and subsequent diagenetic alterations (Milliken et al., 2016; Wang et al., 2024). Critical diagenetic processes include mechanical compaction, clay mineral transformations, quartz cementation, carbonate cementation, feldspar alteration, and organic matter maturation (Baruch et al., 2015). For example, the presence of significant volumes of quartz cements largely enhanced the rock brittle behavior in the Upper Cretaceous Eagle Ford Formation, Lower and Upper Cretaceous Mowry Shale, and Jurassic Haynesville-Bossier Shale.

3. Mechanical properties of brittle minerals

Brittleness index is a parameter to indicate whether the rock would be easy to fracture, and is very important for hydraulic fracturing design. The rock with higher brittle index will be easier to be fractured. In general, rocks with high brittleness index normally have high content of brittle mineral compositions. However, the definition of brittle minerals is controversial. For example, Jarvie et al. (2007) classified only quartz as brittle mineral, while other studies classified quartz, feldspar, and carbonatite as brittle minerals (Ding et al., 2012; Zeng et al., 2013; Li et al., 2018). In 2015, the China Standardization Administration defined quartz, feldspar, carbonatite, and dolomite as the brittle minerals, which is widely accepted and used in China (GB/T 31483-2015). Determining the exact geomechanical values of minerals is an effective method to distinguish these minerals whether they are brittle or ductile. However, the brittle indicator independent from minerals suffers from confining pressure conditions. In other words, rocks with same mineral compositions have varying deformation and failure characteristics. Thus, current brittleness tends to be defined with respect to mechanical properties, such as Young's modulus, tensile strength and fracture toughness. Moreover, utilizing the complete stress versus strain curve, both pre-failure and post failure parameters can be obtained to justify the rock deformation, and infer the brittleness. Compared to the brittleness calculated from mineral composition, mechanical properties-based brittleness provides a road for the rock deformation considering the specific confining and loading conditions.

In recent years, by applying the surface measuring techniques, nanoindentation provides data on the bulk properties of shales using the tools of continuum indentation analysis, reflecting the geomechanical properties of minerals in nanometer to micrometer scales. Particularly, the introduction of nanoindentation can integrate the geomechanical properties with the mineral distribution (Liu et al., 2023). The pyrite has the highest Young's modulus, followed by quartz and feldspar. Organic matter, commonly recognized as the soft materials, has average Young's modulus around 6 GPa, which is far lower than that of the pyrite, feldspar and quartz. The mechanical values of alkaline minerals are similar to those of feldspar. Overall, based on the nanoindentation measurements, pyrite, feldspar, quartz and alkaline minerals can be grouped as brittle minerals, while organic matter can be regarded as ductile materials.

However, because of the measuring scale limitation, the results from nanoindentation fail to be applied directly for engineering application. Some up-scaling methods are supposed to be used, such as Mori-Tanaka homogenization method. In addition, pores and natural fractures are important parts of shales, and could significantly affect the mechanical properties, leading to anisotropic rock mechanical properties. To offset this limitation, the impact of matrix porosity and fracture porosity should be considered during the homogenization process. The recent findings indicate that the suitable upscaling correlation between nano-scale mechanical properties and macroscopic properties provides an alternative way for estimating rock mechanical properties, enhancing the confidence in engineering applications for complex geological conditions.

4. Fracability evaluation of shales

The selection of hydraulic fracturing candidates can be directly justified by the rock brittleness index. However, brittleness calculated from mineral composition or elastic parameters fails to reveal the influence of confining pressure. Moreover, different calculation methods sometimes yield varying results. For example, mineralogy-based methods rely on the quartz-rich assumption may not be suitable for calcite-rich shales. Secondly, the stress and strain changes before or after rock failure are also useful for estimating rock brittleness. However, the rock brittleness index might not be a distinct measure for determining "fracability". Because the fracability is a compressive definition rather than an independent factor. Additional variables, such as natural fracture distribution also affect the fracture geometry, and should be considered in the fracability evaluation.

To choose suitable candidate for hydraulic fracturing, both the fracability modeling and measurements related to fracability are important. Laboratory experiments, well logs, and seismic data are important sources for the fracability evaluation. Although lab measurements could provide essential data such as Young's modulus, Poisson's ratio and fracture toughness, the access to core samples for unstable shales for mechanical measurement is challenging. Nanometer to micrometer scale indentation and scratch methods could overcome this limitation, but upscaling models are necessary due to measurement target size constraints. Well logs and seismic data contribute to fracability assessment by evaluating mechanical properties and enabling continuous or three-dimensional mapping.

Considering the confining pressures effect, the in-situ stress calculation is also important, although it can be calculated based on wire-line well logs and seismic data. Accurate in-situ stress determination involves hydraulic fracturing, borehole breakouts, deviated well information, and drilling-induced fractures are commonly used. Moreover, the in-situ stress experiments, such as differential strain test or acoustic emission provide further insights. Seismic inversion data enhances confidence in the cross well mechanical properties and stress. Nevertheless, the rock's intrinsic capacity based on the well logs and seismic data for the largest possible complex fracture network area fails to consider the natural fracture distribution. In fact, different natural fracture attributes can affect the fracture propagation path or the effects of long-term adequate fracture conductivity on shale gas production. Under the direction of geological data, stochastic modeling, and numerical simulation of the tectonic stress field, the natural fracture modeling should be developed. Furthermore, discrete fracture network modeling is typically utilized to map natural fractures at the reservoir scale, and the model's accuracy should be verified using dynamic drilling and production data. Fracability evaluations primarily focus on rock mechanical properties, such as the brittleness due to limited petrophysical data. Emerging techniques such as the "double sweet spot" approach integrate numerous reservoir parameters and mechanical properties. The double sweet spot can consider the influencing factors on the gas production rather than the fracture geometry.

Direct measurements of geomechanical characteristics must be combined with traditional well logs for robust reservoir fracability measurement. Shale's anisotropy causes differences between vertical and horizontal wells. Vertical wells typically use P- and S-wave sonic velocity to measure elastic impedance's vertical component, neglecting the horizontal velocity and impedance. Since pore pressure and dynamic stress change can be impacted by depletion, dynamic fracability estimation should be used to develop long-term shale gas reserves effectively and efficiently.

5. Summary and perspectives

Shale has complex rock composition and different brittle mineral sources. The petrophysical and mechanical properties of shales with different minerals and rock fabrics are quite different. Lacustrine and marine shales are quite different in mineral composition and sources. In general, lacustrine shales generally have high clay content, and varying contents of carbonate minerals, as well as abundant laminae, however, marine shales are typically characterized by high quartz content, especially the quartz sourced from biogenic silica. Therefore, there are significant differences in the brittleness evaluation method between lacustrine and marine shales, and then the fracability evaluation method would also be different. Based on the summary of this study, some future research needs to be carried out:

1) the genesis and source of brittle minerals in marine, lacustrine and paralic shales;
2) the mechanical properties of the minerals under the true formation conditions;
3) the comprehensive research of fracturing in multiple scales (from micro to macro, from mineral to rock mechanics, from geology to geophysics, from geological evaluation to engineering fracturing, etc).

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Conflict of interest

The authors declare no competing interest.

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