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What controls the mechanical properties of shale rocks? – Part II: Brittleness

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ABSTRACT

Successful stimulation of shale gas reservoirs by hydraulic fracturing operations requires prospective rocks characterized by high brittleness to prevent fast healing of natural and hydraulically induced fractures and to decrease the breakdown pressure required to (re-) initiate a fracture. We briefly reviewed existing brittleness indices (B) and applied several, partly redefined, definitions relying on composition and deformation behavior on various, mainly European black shales with different mineralogical composition, porosity and maturity. Samples were experimentally deformed at ambient and elevated pressures (P) and temperatures (T), revealing a transition from brittle to semibrittle deformation behavior with increasing pressure and temperature. At given composition and deformation conditions, B values obtained from different definitions vary considerably. The change of B with applied deformation conditions are reasonably well captured by most definitions based on the stress–strain behavior, which do not correlate with the fraction of individual phases, e.g., clay content. However, at given deformation conditions, most composition-based indices show similar variations with bulk composition as those derived from stress–strain behavior. At low P–T conditions ($\lesssim$4 km depth), where samples showed pronounced post-failure weakening, B values determined from composition correlate with those calculated from pre-failure stress–strain behavior and both correlate with the static Young's modulus. In this regime, the brittleness concept can help to constrain successful hydraulic fracturing campaigns and brittleness maybe estimated from core or sonic logs at shallow depth. However, long term creep experiments are required to estimate in-situ stress anisotropy and the healing behavior of hydraulically induced fractures.

1. Introduction

In the past decades, the increasing fossil energy demand pushed the exploitation of unconventional hydrocarbon reservoirs, in particular oil and gas shales. Multi-stage hydraulic fracturing stimulations are common practice to enhance the production rate. Successful fracturing campaigns in prospective shale plays with low proppant embedment aim at maximizing the stimulated rock volume (e.g., Wang and Gale, 2009; Berard et al., 2012). Efficient stimulation of the reservoir requires a good knowledge of the rock mechanical properties.

The mechanical behavior of shales may be classified into brittle and ductile (e.g., Nygard et al., 2006; Jaeger et al., 2007; Fjaer et al., 2008; Holt et al., 2011). Brittle shales are expected to contain natural fractures and are more easily fractured by hydraulic stimulation. In contrast, ductile shales are believed to show fast fracture healing and to pose constraints on the mud weight window in order to avoid borehole breakouts (e.g., Rickman et al., 2008; Holt et al., 2011; Mullen and Enderlin, 2012). In petroleum engineering, this distinction in the mechanical response of source rocks is commonly described in terms of rock brittleness or fracability (e.g., Holt et al., 2011, 2015; Yang et al., 2013; Jin et al., 2014), sometimes also termed fragility, penetrability, drillability, or cuttability in mining sciences (e.g., Thuro and Spaun, 1996; Altindag, 2002; Kahraman and Altindag, 2004; Tiryaki, 2006). The opposite behavior is usually denoted as ductility. Unfortunately, no unique definition of brittleness exists and many different index definitions have been proposed to quantify the degree of brittle or ductile deformation behavior (e.g., Hucka and Das, 1974; Andreev, 1995; Holt et al., 2011, 2015; Yang et al., 2013; Jin et al., 2014). According to Andreev et al. 1995, brittleness can be regarded as a material property, where brittle rocks have high mechanical strength and the deformation/failure behavior displays a low degree of inelasticity and strong localization. This is in contrast to

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ductile deformation, which is non-localized on a macroscopic scale. The prevailing deformation mechanisms (i.e., microcracking vs. intracrystalline plasticity) result in a scale dependent mechanical behavior. A rock may respond to mechanical loading brittle on a (grain) microscale, but ductile on a macroscopic (sample) scale (Rutter, 1986). The (ductile) transitional regime between brittle and plastic deformation is called semibrittle (Evans et al., 1990; Evans and Kohlstedt, 1995). Therefore, brittleness depend not only on material properties, like composition, porosity, water content, structure and texture, but also on boundary conditions, as for example loading rate, temperature, effective differential stress and confining pressure.

Because of this complexity, the determination of brittleness of specific shale requires advanced laboratory testing procedures, which are time-consuming and relatively expensive. Accordingly, other empirical definitions of brittleness were proposed that are more easily estimated from borehole or mud logging. These are based on dynamic elastic parameters (Young's modulus and Poisson's ratio, e.g., Grieser and Bray, 2007; Rickman et al., 2008) or composition (fraction of strong versus weak minerals, e.g., Jarvie, et al., 2007; Wang and Gale, 2009), respectively.

We deformed (mainly European) black shales with different composition, maturity and porosity at varying confining pressures, temperatures and deformation rates. The results are described in an accompanying paper (Rybacki et al., 2015) showing that, at preset pressure–temperature conditions, the strength and Young's modulus can be estimated roughly from the volumetric fraction of strong minerals (quartz, feldspar, pyrite), carbonates (intermediate strong fraction in shales), weak constituents (clay, kerogen) and pores. However, at given composition and porosity, the mechanical response and associated brittleness depend on the external conditions (pressure, temperature), which may not be captured by most common brittleness index definitions. Here, we examine the brittleness of shales with varying composition and porosity in response to the applied deformation conditions.

2. Sample materials and experimental methods

The examined black shales comprise 4 different immature to overmature Posidonia shales (Dotternhausen=DOT, Wickensen=WIC, Harderode=HAR and Haddessen=HAD) from Germany and overmature Alum (=ALM) shale from the island of Bornholm (Denmark). In addition, we inspected mature Barnett (=BAR) shale from Texas (USA) and reference samples composed of the main constituents of shales (NOV=Arkansas novaculite, GRA=Westerly granite, GAB=Panzhihua gabbro, FST=Flechtingen sandstone, BST=Bentheim sandstone, LIM=Solnhofen limestone, MAR=Carrara marble, COA=black coal). The shale maturity, described by Vitrinite reflectance, varies between 0.6 and 3.6 VRr% and the porosity between 0.6 and 11 vol%, measured by mercury intrusion porosimetry (MIP). Note that the total connected porosity, estimated from He-pycnometry, is usually 1–2 vol% higher compared to MIP values, but for Alum shale up to 8 vol% higher. The shale composition, determined by X-ray diffraction analysis (XRD), is quite variable with 17–62 vol% clay (illite, illite-smectite, kaolinite), 0–50 vol% carbonates, 7–46 vol% quartz, 0–10 vol% feldspar, and 0–7 vol% pyrite. The total organic carbon content (TOC) is 2–22 vol%. Most Alum samples are poor in carbonates with a high amount ($\approx$60–70 vol%) of mechanically weak components (clay, kerogen) and about 30–40 vol% strong minerals (quartz, feldspar, pyrite). In contrast, Posidonia shales contain a high fraction of carbonates ($\approx$25–45 vol%), $\approx$40–60 vol% weak and $\approx$10–20 vol% strong phases, whereas Barnett shale consists of $\approx$10 vol% carbonate, $\approx$40–50 vol% weak and $\approx$30–50 vol% strong components (Fig. 1). The composition of the reference samples and

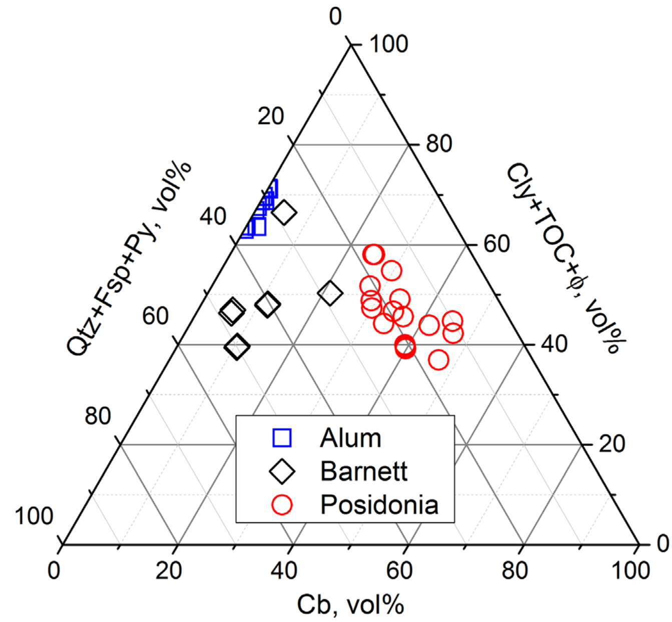

Fig. 1. Ternary diagram of shale composition (in vol%). Mechanically strong phases are quartz (Qtz), feldspar (Fsp) and pyrite (Py), Cb is carbonate (intermediate strong), and weak components are clay (Cly) and kerogen (TOC). Φ is porosity.

some specific shale samples used for triaxial compression are given in Table 1.

The transverse isotropic shale samples contain distinct bedding planes that are rich in organic matter with subparallel oriented pyrite flakes and calcareous bands. The grain size is typically $< 5\ \mu m$. A more detailed description of the composition and microstructures is given by Rybacki et al. (2015). The water content of Posidonia and Barnett shale was $\approx$1–2 wt% and of Alum shale $\approx$4 wt%, determined by drying of samples until zero weight loss. For axial compression experiments, cylindrical samples were prepared with dimensions of 50 mm length and 25 mm diameter or 20 mm length and 10 mm diameter for tests at room and elevated temperatures, respectively. Brazilian disc tests were performed on samples of 30 mm diameter and >15 mm length.

Most tests at ambient temperature were performed at constant deformation rates of 0.2 mm/min using a stiff, servo-hydraulically controlled deformation apparatus (MTS). The tensile strength, σ_T, was determined from Brazilian disc tests in accordance with the ISRM suggested method (Bieniawski and Hawkes, 1978). The uniaxial compressive strength, σ_C, and associated strain were determined from the recorded load displacement data, corrected for the system stiffness. Triaxial strength (peak stress), σ_{max}, values were measured at (oil) confining pressures, P, between 17.5 and 70 MPa, using rubber-jackets for sealing. Triaxial deformation experiments at elevated temperature were performed in a Paterson-type deformation apparatus (Paterson, 1970) at constant strain (deformation) rates, using argon gas as confining pressure medium. Measured forces were corrected for the strength of copper sleeves used to jacket the samples and converted to axial stress assuming constant volume deformation. Axial displacements were corrected for the system compliance. The estimated error of stress and strain values is $<4\%$. Because of the low stiffness of the Paterson apparatus and using copper as jacket material, the Young's modulus and post-failure deformation behavior measured at elevated temperature is less accurate with an estimated error $<20\%$.

3. Quantification of brittleness

Various suggested brittleness indices are summarized in the appendix, yielding more than 36 different definitions that are