Journal of Natural Gas Science and Engineering 43 (2017) 110–123

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Experimental investigation of Sinian shale rock under triaxial stress monitored by ultrasonic transmission and acoustic emission

Xiaying Li [a, b], Xinglin Lei [c], Qi Li [a, *], Xiaochun Li [a]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics (IRSM), Chinese Academy of Sciences, Wuhan 430071, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, 305-8567 Ibaraki, Japan

A R T I C L E I N F O

Article history:
Received 1 December 2016
Received in revised form
18 March 2017
Accepted 19 March 2017
Available online 4 April 2017

Keywords:
Sinian shale
Sichuan Basin
Velocity anisotropy
Brittleness
Ultrasonic transmission
Acoustic emission

A B S T R A C T

To investigate the acoustic and mechanical properties of shale gas reservoir rocks, fracture experiments under triaxial compression were conducted using Sinian shale samples collected from the Sichuan Basin and cored along an angle of ~15° with respect to bedding orientation. Ultrasonic transmission (UT) and Acoustic emission (AE) were used to monitor the response of anisotropic wave velocity and fracture behavior to elevated stress. X-ray CT (computed tomography) scan was used to explore the heterogeneous structure and geometric property of the fracture zone that ultimately developed in the sample. The evolution of microstructure such as closure of pores, development of microcracks and formation of macro fractures at elevated stress is likely responsible for the observed responses of elastic wave velocity and AE activity. During the hydrostatic compression stage, the closure of cracks and pores leads to a little bit of increase of velocity and a small number of AE events. As the mean effective stress further increases, there is no significant change in the microstructure of shale sample derived from the non-response of velocity to elevated stress. During the dynamic fracture stage, the generation of macro-fracture along the bedding plane accounts for the decrease of velocity as well as the rapid increase of AE activity. Our results indicate that the Sinian shale of the Sichuan Basin is characterized by weak anisotropy and strong heterogeneity in core scales. The intrinsic anisotropy keeps almost unchanged to the elevated stress, while significant increase in velocity anisotropy is induced by shear fracture. Moreover, the fracture experiments show that the shale sample performs a purely brittle fracture behavior, which is beneficial for the hydraulic fracturing stimulation of shale gas reservoirs. Both AE hypocenters and X-ray CT scan image show that the deformation and fracture process correlates strongly with the bedding structure in the sample.

1. Introduction

Because excessive exhaustion of conventional fossil energy and large demand for energy as a result of the rapid development of global economy, the exploration and exploitation of shale gas have become imperative over the past several decades. China has the largest potential shale gas reserves and the biggest energy market in the world (Wang et al., 2014). The Sichuan Basin in southwestern China has been identified as one of the areas with the greatest potential for shale gas development (Jiang et al., 2010; Zou et al., 2011). A key target for shale gas exploration in South China, the Lower Silurian Longmaxi Formation has been studied as a source rock in great detail for several years (Chen et al., 2013; Huang et al., 2012; Lv et al., 2013; Wang et al., 2012; Yang et al., 2014; Zou et al., 2010). Besides the Silurian formation, the Sinian shale is another potential target formation in the Sichuan Basin (Wei et al., 2013; Zou et al., 2014). However, existing reports mainly consider its lithological characteristics, depositional environment and evaluation of shale gas reserves (Dai et al., 1999; Gen et al., 2008; Liu et al., 2009). The acoustic and mechanical properties of the Sinian shale have not yet been systematically investigated.

Anisotropy has been recognized as a significant factor for seismic exploration and hydraulic fracturing (Pan et al., 2015; Yang et al., 2015, 2016; Zhou et al., 2016). Shale is characterized by high anisotropy since bedding structure is well developed in shale

* Corresponding author. Xiaohongshan 2, Wuchang, Wuhan 430071, China.
E-mail address: qli@whrsm.ac.cn (Q. Li).

http://dx.doi.org/10.1016/j.jngse.2017.03.035
1875-5100/

formations (H. Einstein, 2015; Martin et al., 2015). Such strong bedding structure is well known as a significant factor for velocity anisotropy. The degree of shale anisotropy under different stress environment need to be well understood for designing hydraulic fracturing processes, and updating seismic velocity models for micro-seismic monitoring (Liu et al., 2016). Velocity measurements on a suite of shales performed by Johnston and Christensen (1995) indicated that these shales can be modeled as transversely isotropic (TI) materials with the main symmetry axis perpendicular to bedding plane. The alignment of clay mineral is cited as the underlying cause of the anisotropy of shale. The effect of clay-particle interaction on the anisotropy of shale had been detailed investigated by Sayers (2005) in terms of the Thomsen's parameters. Elastic wave velocity was measured for Kimmeridge shale to investigate the influence factors of elastic anisotropy, such as single crystal elastic properties, grain shapes, preferred orientation, and volume and shapes of pores (e.g. Vasin et al., 2013). Both velocity and attenuation anisotropy of P- and S-wave were measured in dry shale sample from Whirby, UK. The result shows that the degree of anisotropy can be large as 70% and the change of P-wave velocity is more apparent than that of S-wave (Zhubayev et al., 2015).

Acoustic and mechanical properties are sensitive to the evolution of microstructure and damage in rocks (Liu et al., 2016; Wang et al., 2007, 2010a, 2010b; Yang and Zoback, 2015). P-wave velocity is found to be more sensitive to the development of pores and microcracks than S-wave under changing stress field (Zhubayev et al., 2015). Therefore, continuous ultrasonic measurements under triaxial compression are widely used for the estimation of the evolutions of velocity anisotropy and microstructure of shale sample. Dewhurst and Siggins (2006) performed a set of experiments on Muderong shale with the maximum principle stress parallel to bedding plane and then evaluated the response of ultrasonic velocity to anisotropic stress field. Kuila et al. (2011) investigated the ultrasonic velocity response of low porosity shales with orientation of bedding plane normal to the maximum principal stress to both isotropic and anisotropic stress fields under multi-stage triaxial tests. The result demonstrates that the intrinsic anisotropy caused by laminations and particle alignment can be further modified by the application of differential stress. Elastic velocity and anisotropy were measured by Piane et al. (2011) on two shale samples with different bedding orientations to the maximum principle stress under undrained multistage triaxial tests. In vertically cored sample (the direction of the maximum stress is normal to bedding plane), vertical velocity (V_{pv}) increases and horizontal velocity (V_{ph}) decreases monotonically with increasing effective stress, inducing a decrease of velocity anisotropy. The reverse occurs when the maximum stress is parallel to the fabric, where V_{ph} increases and V_{pv} decreases with increasing effective stress. Anisotropy of elastic wave velocity decreases with applied axial stress perpendicular to bedding plane within both dry and wet shale samples (Sarout and Guéguen, 2008). However, the anisotropy of the wet sample is always lower than that of the dry one.

The above researches show that the stress-induced ultrasonic anisotropy depends on the magnitude of the principal stress, and its orientation with respect to the bedding plane of the sample. However, most experiments were performed with the maximum axial stress either normal or parallel to the bedding plane of the test sample. Thus a problem raises that what is the response of velocity anisotropy to elevated stress when the axial stress is skewed to the bedding plane. Furthermore, previous attempts were primarily devoted to the response of velocity anisotropy before fractured. Studies on the response of anisotropy induced by the formation of macro fracture are limited.

Microseismicity is another indicator for the evolution of microcracks and damage. In brittle rocks, microcrack activity, which can be monitored by AE technique, leads to macroscopic inelastic strain (Amitrano, 2003; Fortin et al., 2009; Ishida et al., 2012; Stanchits et al., 2011). Rock failure begins with microcrack activity, and fracture initiation and growth (e.g. Heggheim et al., 2005). In addition, the orientation of bedding structure under a given stress field plays a dominate role in the fracture process and in determining fracture zone properties (Fjær and Nes, 2014; Lei et al., 2013b; Meier et al., 2015; Wasantha et al., 2014). Thus, detailed spatiotemporal distribution of AE events, in combination with X-ray CT scan image of fractured sample, will be helpful in elucidating the evolution of microcracks and the geometry of the final fracture.

The purpose of this paper is to investigate the acoustic and mechanical properties of Sinian shale from the Sichuan Basin in response to differential stress based on continuous ultrasonic transmission (UT) measurement and acoustic emission (AE) monitoring. The remainder of this paper is organized as follows. First, a short description of the Sinian shale reservoir in the Sichuan Basin and the characteristics of sample are presented. Then, the experimental apparatus and procedures are followed. The experiment results of UT measurement and AE monitoring will be analyzed. Finally, an estimation of the evolution of induced microstructure under the elevated stress field is in the discussion.

2. Geological background and experimental procedure

2.1. Geological background

The Sichuan Basin, located in southwestern China, is a tectonically stable and structurally complex basin that develops on the Yangtze craton (Liu et al., 2009; Wang et al., 2014; Zou et al., 2011). The basin covers an area of over 18×10^4 km^2 with sedimentary rocks ranging from 6000 to 12,000 m in thickness (Zou et al., 2014). As aforementioned, it is a prolific hydrocarbon region and is currently the largest gas-producing area in China. Thick marine formation deposits are located widely around the Sichuan Basin spanning the Sinian to Middle Triassic period. Sinian shale, developed in the Dengying and Doushantuo Formation with the thickness ranging from 300 to 1200 m, has been considered as a potential target for shale gas exploration (Dai et al., 1999; Wei et al., 2013; Zou et al., 2014). To evaluate the exploitation potential of Sinian shale formation, Wei et al. (2013) had investigated the tectonic characteristics, sedimentary environment, and preservation condition of Sinian shale formation. Furthermore, four favorable prospective areas were selected for future shale gas exploitation.

The Sichuan Basin is a relatively stable region in China showing very low level of background seismicity. However, during the past three decades, a number of seismic sequences had been observed with sizable earthquakes ranging up to M4~5. Their timing, location and occurrence pattern involved in statistical models, convincingly suggest that these sequences were induced by injections of unwanted water in deep wells in depleted gas fields (Lei et al., 2008, 2013a). Detailed studies on some recent and well monitored cases demonstrate that most events, particularly larger ones, mirror the reactivation of pre-existing faults (including joints and fractures) in the sedimentary formations or faults underlying/overlying the reservoir (Lei et al., 2013a). Following the breakthrough of the shale gas industry in China in 2010, fracking-induced earthquakes are suspected to be partially responsible for the increase in seismic activity in recent years. Earthquakes with sizeable magnitude up to M_L4.3 have been observed in a fracking site.