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Investigation of the P- and S-wave velocity anisotropy of a Longmaxi formation shale by real-time ultrasonic and mechanical experiments under uniaxial deformation

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ABSTRACT

Characteristics of the P- and S- velocities anisotropy, and the velocity-pressure dependency characteristics in organic-rich shale are still incompletely understood in rock-physics literature. As a result of the increasing importance of the role of shale in unconventional formations, a more thoughtful study of its mechanical and ultrasonic properties is needed. This work is devoted to Longmaxi shales that experienced real-time uniaxial deformation in the laboratory. Cylindrical shale samples obtained by drilling at inclinations of 0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively, are used to perform a series of Uniaxial Compressive Strength (UCS) tests. The experimental results suggest that pronounced bedding planes have significant influence on the mechanical properties and velocity responses. The P- and S-wave velocity decrease with increasing inclination, and the pronounced bedding planes of shale govern the intrinsic P- and S-wave velocity anisotropy. With the increasing applied axial stress, P-wave velocity increases and S-wave velocity first increases and then decreases. The closure of pores and micro-cracks was identified as the extrinsic source governing the pressure sensitivity of the P- and S-wave velocity. The decrease of the S-wave velocity is due to the rapid propagation and growth of the crack density in shale, and the corresponding stress point is in good agreement with the crack damage stress in the stress-volumetric curves. The link between the P- and S-wave velocities against stress presents a logarithmic and linear relationship with good correlation, respectively. Finally, from the macroscopic failure morphology analysis and the post failure X-ray computed tomography scanning, the anisotropy failure modes are further discussed. Aided by the contributions of the velocity anisotropy of shales, it is possible to establish mechanical constructive equations using rock-physical parameters to predict borehole stability and hydraulic fracturing.

1. Introduction

The organic shale reservoirs demonstrate distinct anisotropic behaviors due to the existing platy clay minerals within the rock matrix. Because of the subtle distinction in clay content and other minerals, plenty of fine-scale lamination or layering develops in shale, in the form of fine scaled alignment. The appearance of these laminas (bedding planes) leads to the mechanical property anisotropy, and to many fundamental rock properties including strength, modulus, permeability, acoustic velocity, Poisson's ratio, electrical resistivity, etc. The internal structure of shale usually controls the borehole stability issues that cause serious economic loss. In addition, due to the low matrix permeability, a pressure drop in the shale reservoirs is good for the formation of a large scaled fracturing network to produce hydrocarbons at an economic rate. Fortunately, the anisotropic behavior can help create a complex fracture network rather than the conventionally planar fractures. The shale mechanical properties have significant influence on the stimulation of the fracture network and thus improve the shale gas productivity (Rybacki et al., 2015, 2016).

When we attempt to predict the behaviors of shale, the anisotropic attribute should be deeply considered. A large amount of previous experimental investigations have been performed that characterize the

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List of symbols

UCS	Uniaxial Compressive Strength test
UPV	Ultrasonic pulse velocity
V_P	P-wave velocity
V_S	S-wave velocity
SEM	Scanning electron microscopy
σ	Axial stress
E	Elastic modulus
v	Poisson's ratio
ε_v	Volumetric strain
X-ray CT	X-ray Computed tomography

Fig. 2. The layered structure in shale sample.

deformation and failure behaviors of various clayey rocks. For those experiments, the shale sample was prepared in different orientations with respect to the bedding planes. Many scholars have conducted a series of laboratory compressive tests (Masri et al., 2014; Rybacki et al., 2015, 2016; Wang et al., 2016), tensile tests (Mokhtari et al., 2014), three point bending tests (Heng et al., 2015a), direct shear tests (Heng et al., 2015b,c), and numerical tests (Mokhtari et al., 2013; Suarez-Rivera et al., 2013) on the shale outcrop and reservoir specimens. They have not only studied the macroscopic failure mechanism of shale under static strain rate (Sone and Zoback, 2013a,b; Masri et al., 2014), but also medium strain rate (Rybacki et al., 2015), high strain rate (Liu et al., 2015), cyclic loading and unloading (Wei et al., 2015), and high temperature (Islam and Skalle, 2013; Masri et al., 2014) conditions. After a literature review, it is apparent that few studies have been published about the investigation of the anisotropic mechanical properties of shale using a real-time non-destructive inspection technique to monitor damage evolution, meso-structure variations, formation of shear band, etc.

Ultrasonic techniques, known to be maneuverable and non-destructive for apply both for in-situ and laboratory conditions, are promising for geophysical interpretation applications, including the interpretation of mechanical and dynamic elastic shale behaviors. The laboratory acoustic test results are good for interpreting well logs and seismic data, and to design wellbore drilling, hydraulic fracturing, and production predictions. It is critical to evaluate the acoustic behavior of shale formations and to utilize the field data for determining an accurate in-situ stress state and assigning reliable mechanical properties to the formations of interest (Sarout and Guéguen et al., 2008a, b; Dewhurst et al., 2011; Allan et al., 2015). The velocity and anisotropy of shales have both been studied in detail in the laboratory (Podio et al., 1968; Lo et al., 1986; Johnston, 1987; Hornby et al., 1994; Vernik and Liu, 1997) and in-situ (White et al., 1983; Winterstein and Paulson, 1990). These results show that porosity, smectite, fabric orientation, kerogen content, microfractures, and physicochemical interaction with pore fluids are the main factors affecting the anisotropy. Velocity anisotropy of the shale subsurface is identified as the main reason resulting in significant problems for geophysical interpretation, and to understand the dynamic elastic, it is necessary to explore the anisotropy in detail. However, most tests do not link the correlation of P- and S-wave velocities, attenuation, and geomechanical characteristics. Lo et al. (1986) have studied the P-, SH-, and SV-wave velocity characteristics for Chicopee shale using the ultrasonic transmission method, and during the test, external load is loaded in different directions, and the maximum confining pressure is up to 1000 bars. Their experimental results show the combined effects of mineral grain orientation and that the existence of pores or cracks is the main reason leading to elastic anisotropy. Furthermore, with the increase of confining pressure, the elastic anisotropy decreases accordingly. Sarout and Guéguen (2008a, b) conducted laboratory experiments to explore the velocity anisotropy in deformed shales, and discussed the evolution process of elastic wave velocities. Also, a micromechanical model has been proposed to interpret the experimental data obtained on both wet and dry shale samples. Dewhurst et al. (2011) performed multiple stage triaxial tests to study the ultrasonic and geomechanical characterization of a Norwegian Sea shale. They found that loading orientation with respect to bedding plane was an important controlling factor resulting in the anisotropy of

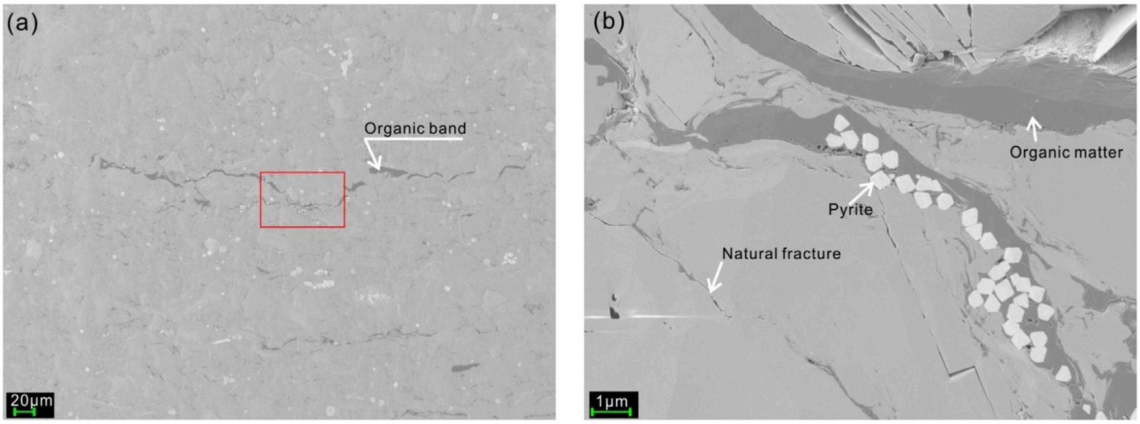

Fig. 1. SEM imaging of shale sample vertical to the direction of bedding face, respectively. Figure "b" corresponds to the magnified region in figure "a". Pyrite and organic matter can be visible clearly in the picture.

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