Impact of water saturation on the mechanical properties and elastic anisotropy of the Whitby Mudstone

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Introduction

Mudstones are of interest in various industries, including the petroleum and underground repository industry, because they can act as a source, reservoir, seal, and/or flow barrier. Knowledge and understanding of the mechanical and physical properties of mudstones is crucial for seismic imaging, the development of hydrocarbon resources, and the safety assessment of underground repositories.

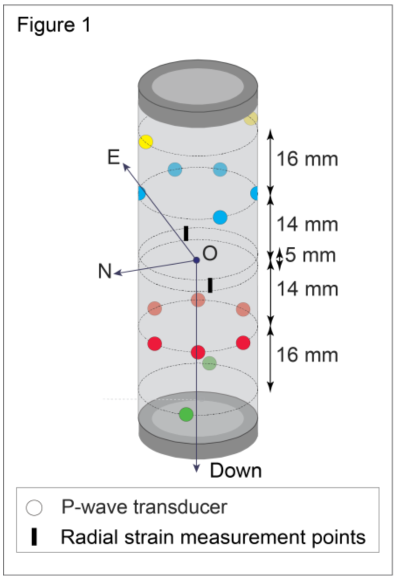
These low-permeability rocks are often anisotropic, which complicates the predictions of their elastic properties. This results in significant issues in depth conversion for sweet spot mapping in seismic exploration, or in imaging geological structures. Previous studies reported velocity measurements and elastic anisotropy of mudstones (e.g., Vernik and Nur, 1992). However, the core plugs used in these studies were often not preserved and the laboratory testing was carried out without pore pressure control, which is critical for obtaining realistic estimates of the mechanical properties and elastic anisotropy of mudstones (Dewhurst and Siggins, 2006). The mechanical and physical properties of mudstones are highly dependent on water saturation. For instance, the loss of natural pore water in clay-rich rocks might induce damage, affecting their mechanical and transport properties significantly. Although the impact of dehydration on the bulk properties of mudstones has been studied and reported in the literature, the effect of water saturation on the elastic anisotropy has attracted far less attention.

This study examines the impact of water saturation on the mechanical properties and elastic anisotropy of mudstones in the laboratory. Triaxial compression tests are performed on Whitby Mudstone core plugs with different degrees of water saturation under effective pressures of 15 MPa. Axial and radial strains are measured during loading. P-wave velocities are monitored along multiple ray paths during the experiment. The evolution of Thomsen's anisotropy parameters and the orientation of the symmetry axis are derived using a recently published inversion technique (Kovalyshen et al., 2017). The influence of water saturation in the Whitby Mudstone on (i) the quasi-static Young's modulus and Poisson's ratio, (ii) the strength properties (peak stress), and (iii) dynamic elastic properties and anisotropy are documented in this study.

Materials and Methods

The mudstone samples originate from a wave-cut platform of the Whitby Mudstone Formation (WMF), United Kingdom. Mudstone blocks were collected from the same horizon in the outcrop using a hammer and a chisel. The shale blocks were stored in seawater from the moment of recovery to prevent them from drying. Cylindrical specimens, 38 mm in diameter and 80 mm in length, were cored out of the larger blocks normal to the bedding plane. Each specimen was equilibrated for two months at room temperature in a constant relative humidity atmosphere (85%, 75%, and 35%) within desiccators. The fully saturated core plug was stored in seawater.

After equilibration, triaxial compression tests were performed on all mudstone specimens at 15 MPa effective confining pressure. A pore pressure of 2 MPa and a confining pressure of 17 MPa were used for the fully saturated specimen, and no pore pressure and a confining pressure of 15 MPa were applied for the partially saturated specimens. The triaxial loading was carried out at a strain rate of 10^{-7} s^{-1}. The axial deformation of the specimen was monitored with a pair of diametrically opposed Linear Variable Differential Transducers (LVDTs) attached to the top and bottom platens supporting the specimen within the triaxial stress vessel. The radial deformation was measured at the specimen's mid-height through the Viton sleeve isolating the specimen from the confining oil thanks to a bending brass half-ring equipped with strain gages. These data were used to determine the quasi-static Young's modulus and Poisson's ratio for a loading applied normal to the bedding plane (i.e., E_3 and ν_{13}). The peak stress at failure (strength) of each specimen is also determined for this orientation. In addition, an array of 17 ultrasonic P-wave transducers (diameter 8mm and central resonant frequency ~ 0.5 MHz) was attached to the specimen to measure ultrasonic wave velocities along multiple ray paths (Figure 1). A P-wave velocity survey was performed every five minutes while loading the specimen. Each survey consists of 17 shots, one from each transducer acting as a source. During each shot, the remaining 16 transducers act as receivers and the transmitted signals (waveforms) were recorded with a sampling rate of 10 MHz. The method of P-wave inversion presented by Kovalyshen et al. (2017) was used to determine Thomsen's elastic anisotropy parameters (α_0, β_0, γ, ε) and the orientation of the symmetry axis assuming a transversely isotropic elastic medium.



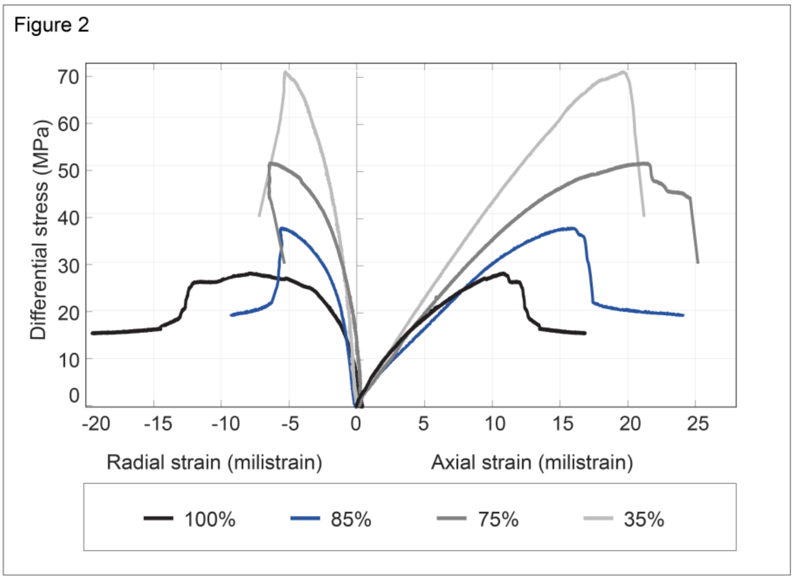


Fig. 1: Position of the ultrasonic P-wave transducers on the cylindrical mudstone specimen
Fig. 2: Stress-strain behaviour of the mudstone specimens equilibrated in various relative humidity atmospheres

Preliminary results

Stress-strain relationships obtained from the triaxial tests were used to determine the quasi-static elastic properties and the peak stress value for the four states of saturation achieved in this study (Fig. 2). The quasi-static Young's modulus (E_3) and Poisson's ratio (ν_{13}) were calculated from the most linear part of the axial stress-axial strain and axial stress-radial strain curves, respectively. Note that linear domain was more difficult to define in the case of the fully saturated specimen based on the stress-strain curve only. Table 1 summarises the rock strength and quasi-static elastic properties for the different saturation states studied. The peak stress increases with decreasing saturation. The Poisson's ratio is relatively high for the fully saturated sample (0.34) and has a value of ~ 0.20 at lower saturation. The impact of water saturation on the ultrasonic P-wave velocity and elastic anisotropy of the Whitby Mudstone will also be presented at the conference.

Table 1: Elastic properties and peak stress of the tested mudstone specimens

Relative humidity (%)	Peak stress (MPa)	Young's modulus (GPa)	Poisson's ratio (-)
100	28	3.8	0.34
85	38	2.8	0.19
75	52	3.5	0.21
35	71	4.2	0.18

References

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