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The Effect of Temperature and Pressure on the Rock Mechanical Behaviour of the Whitby Mudstone Formation, UK

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SUMMARY

We studied the rock mechanical behaviour of the outcropping Whitby Mudstone Formation shales (Toarcian Age) under varying temperature and confining pressure conditions, focusing on strength and elastic moduli. We compared the rock mechanical properties of the Whitby shale to published data of time and depositional equivalent shales from Northern Europe and producing shales from the US. We performed uniaxial and triaxial tests in order to constrain the effect of temperature and pressure on the mechanical behaviour of the shale. We loaded the samples normal to the bedding plane under room humidity conditions. We performed uniaxial tests at room temperature and zero confining pressure, whereas we applied confining pressure in several steps up to 50 MPa and considered temperature values between 20-150°C during triaxial tests. Ultimate strength and elastic moduli are strongly influenced by mineralogy, temperature and pressure. An increase in temperature enhances the deformability, whereby the Young's Modulus and ultimate strength decreases. With an increase in confining pressure, Young's Modulus and ultimate strength increases, whereas the Poisson's ratio decreases.

Introduction

Due to continuously increasing demands for hydrocarbons, the exploitation of unconventional shale-gas reservoirs has strongly increased in recent years, particular in North America (e.g., Rahm 2011; Rybacki *et al.* 2015). These reservoirs are characterized by their anisotropy and low permeability and often hydraulic fracturing is needed to allow sufficient gas production.
In Northern Europe, the Early Jurassic (Toarcian Age) shales are considered as potential unconventional hydrocarbon reservoirs (e.g., Houben *et al.* 2014; Houben *et al.* 2016). Several criteria have been developed for the assessment of potential shale gas plays, including mineralogy, petrology, and rock mechanical properties (strength, elastic moduli) (e.g., Britt and Schoeffler 2009). Understanding the mechanical properties of these rocks are important for the assessment of well bore stability (e.g., Niandou *et al.* 1997; Rybacki *et al.* 2015) and determination of fracture initiation and propagation in shales (e.g., Josh *et al.* 2012).

Here, we present the rock mechanical properties, focusing on strength and elastic moduli of Toarcian Age shale-gas reservoir rocks. Rock mechanical properties were obtained through laboratory experiments and compared to published data (Niandou *et al.* 1997; Sone and Zoback 2013; Masri *et al.* 2014; Rybacki *et al.* 2015). Deformation experiments were conducted on rocks from the currently outcropping Whitby Mudstone Formation (Toarcian Age) (UK). Experiments were performed at varying confining pressure (P_{conf}) and temperature conditions. The Whitby Mudstone Formation is time equivalent to other potential unconventional gas reservoirs in Northern Europe (Zhubayev *et al.* 2016). We present the Young's Modulus, Poisson's ratio, and compressive strength of the Whitby shale in order to constrain the dependency of these mechanical parameters on the experimental conditions and mineralogy. Rock mechanical data from time and depositionally equivalent shales were obtained from literature for both European and US shales. These shales include the Posidonia shale (Germany) (Rybacki *et al.* 2015) and Tournemire shale (France) (Niandou *et al.* 1997; Masri *et al.* 2014) for the Toarcian Age shales in Northern Europe and Barnett shale and Haynesville shale (Sone and Zoback 2013) from the US. We focus on temperature, confining pressure and mineralogical effects on the mechanical behaviour of the shales.

Methods

Sample Description
The investigated Whitby shale samples were collected at different heights from outcrops along the cliff coast north of Whitby (UK). These rocks are time and depositional equivalents to the North European potential unconventional resource shales (Houben *et al.* 2014; Houben *et al.* 2016; Zhubayev *et al.* 2016). To prevent the samples from drying, the rocks were packed in cling foil. The sample mineralogy is obtained by X-Ray Fluorescence (XRF) measurements.

Core samples were produced manually. The samples were plan parallel with a 30mm diameter and 60mm length. Firstly, we carefully cut cubic-shaped subsamples out of the larger mudstone blocks using a sawing machine. Secondly, we sanded these subsamples manually into cylindrical samples (Fig. 1a).

Figure 1 *(a) Photograph of the Whitby shale samples. (b) Loading orientation and bedding plane of the shale sample (Modified from Zhubayev et al. 2016).*

Experimental Procedures
We conducted uniaxial and triaxial tests under room humidity conditions. Uniaxial tests were performed at room temperature, and the temperature ranged between 20 – 150°C during the triaxial tests. All samples were loaded perpendicular (θ=90°) to the bedding plane (Fig. 1b). We conducted the uniaxial tests under a controlled axial strain rate of 10^{-6} s^{-1}.

Triaxial tests were conducted in a steel-bodied pressure cell, referred to as the TerraTek cell (Dong 2010). This cell is designed to perform triaxial tests under different temperature and pressure conditions. The samples were deformed under triaxial pressure conditions. The piston of a high-pressure pump applies a stress on the sample. Confining pressure is applied on the sample by filling the cell with silicon oil before the actual test. An impermeable Teflon sleeve enclosed the cylindrical samples to prevent intrusion of silicon oil. Displacement transducers in both axial and lateral directions measured strain in the sample.
First, the confining pressure was applied in several steps up to 50 MPa and held constant while the axial differential load was increased. Different temperature values (20-150 °C) were considered. To obtain several measurements of static elastic properties, the axial pressure was unloaded and reloaded between each confining pressure step. Finally, failure of the sample was reached to determine the ultimate strength of the rock sample.

Results

Mineralogy
XRF measurements show that the mineralogy of the Whitby shale varies within the formation (Fig. 2). Compared to the time and depositional equivalent Posidonia shale it turns out that the Whitby mudstone is more clay rich, whereas the Posidonia shale is more carbonate rich. Producing US shales such as the Barnett shale and Haynesville shale are generally more silica rich.

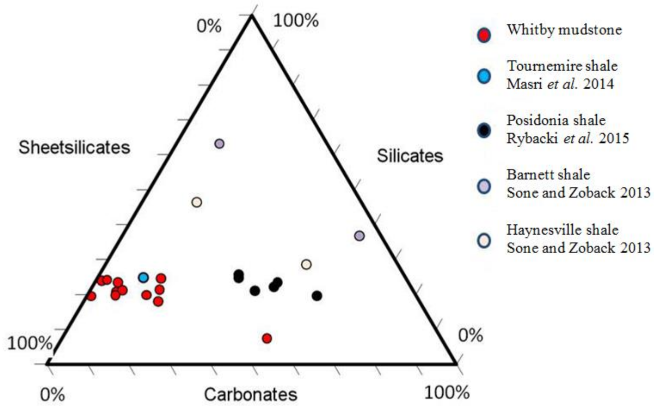

Figure 2 *Ternary plot representing our sample material (Whitby mudstone). For reference, other North European Toarcian Age and US shales are included.*

Uniaxial tests
The experimental results obtained from uniaxial compression tests (i.e. P_{conf} = 0 MPa) at ambient pressure and temperature on Whitby shale samples are shown in Figure 3. Within the Whitby Mudstone Formation, the Young's Modulus varies between 10 and 20 GPa, the unconfined compressive strength values between 60 and 75 MPa, and the Poisson's ratio is between 0.2 and 0.4 (Fig. 3a, 3b, 3c). However, the Young's Modulus values for the Posidonia shale (Germany) are lower (between 3 and 9 GPa), whereas the unconfined compressive strength values are higher (between 80 and 230 MPa) (Fig. 3a, 3b) (Rybacki *et al.* 2015). Young's Modulus and ultimate strength values for the Barnett and Haynesville are generally higher compared to the North European shales (Fig. 3a) (Sone and Zoback 2013). No clear relation was observed between the Young's Modulus and ultimate strength.

Triaxial tests

Rock mechanical data obtained from triaxial tests are shown together with the uniaxial tests in Figure 3. Triaxial tests on the Whitby shale are currently under construction. The relation between confining pressure, Young's Modulus, ultimate strength and Poisson's ratio for the different shales (Whitby shale (this research), Posidonia shale (Rybacki *et al.* 2015), Tournemire shale (Niandou *et al.* 1997; Masri *et al.* 2014), US shales (Sone and Zoback 2013)) are shown in Figure 3a, 3b, and 3c respectively. The mechanical behaviour of the North European shales of Toarcian Age is strongly dependent on pressure and temperature. With increasing confining pressure, both the ultimate strength of the rock and Young's Modulus increases (Niandou *et al.* 1997; Masri *et al.* 2014, Rybacki *et al.* 2015). Young's Modulus remains relatively stable at confining pressures above 100 MPa (Rybacki *et al.* 2015). Poisson's ratio, however, decreases with increasing confining pressure (Masri *et al.* 2014). With increasing temperature, the shale samples show a decrease in ultimate strength between 20 and 400°C (Rybacki *et al.* 2015). Young's Modulus also decreases with increasing temperature (Lempp *et al.* 1994; Rybacki *et al.* 2015).

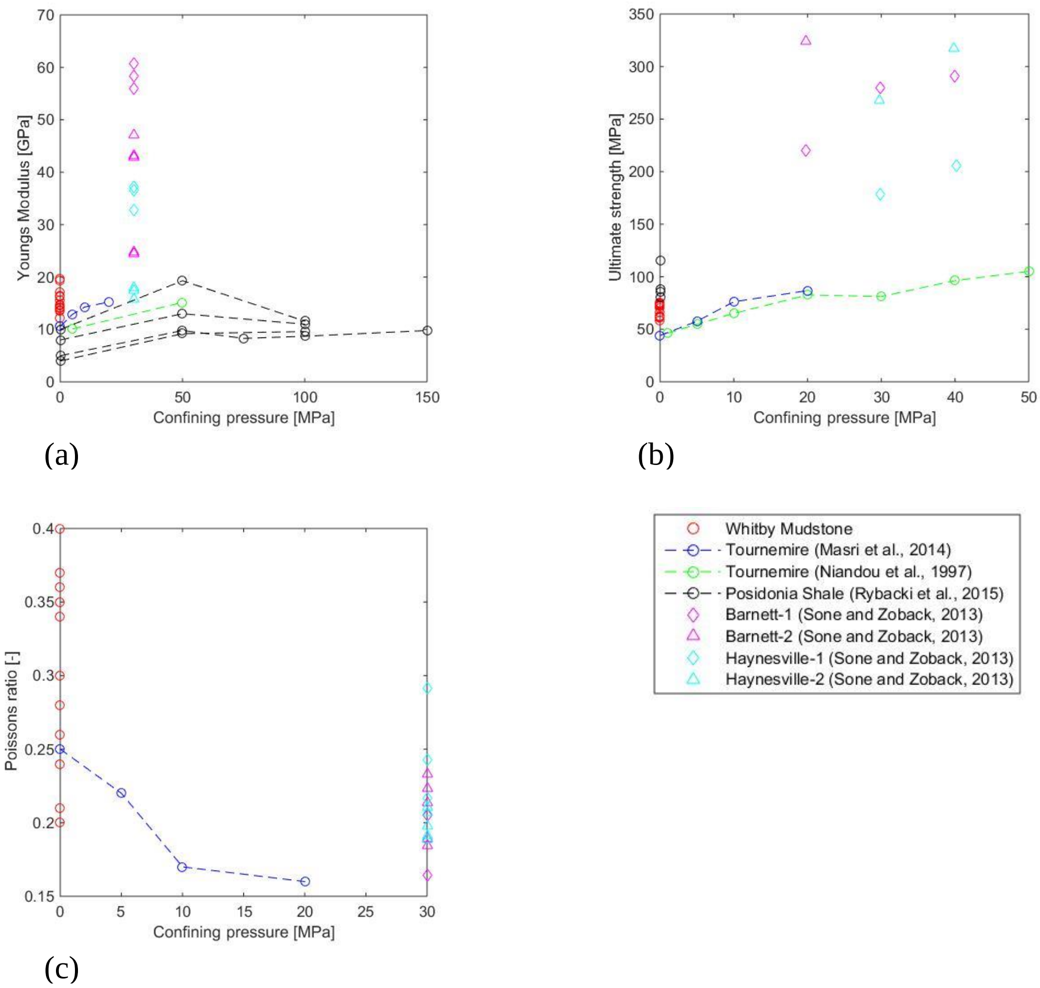

Figure 3 *Relation between confining pressure, Young's Modulus, Ultimate strength and Poisson's ratio from uniaxial and triaxial tests. (a) Confining pressure versus Young's Modulus. (b) Confining pressure versus Ultimate strength. (c) Confining pressure versus Poisson's ratio.*

Conclusions

The effects of pressure and temperature on the mechanical behaviour of shales from different origins have been investigated by uniaxial and triaxial compaction tests. Up to now all samples were loaded normal to the bedding plane. The anisotropic Whitby Mudstone Formation has a relatively high clay and low carbonate content compared to the time equivalent Posidonia shale. Laboratory tests on the Whitby shales show that the values of rock mechanical properties change within the formation, but also between the different Toarcian Age shales. The mechanical behaviour strongly depends on pressure and temperature. An increase in temperature enhances the deformability, whereby the Young's Modulus and ultimate strength decreases. With an increase in confining pressure, Young's Modulus and ultimate strength increases, whereas the Poisson's ratio decreases.

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