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Potential permeability enhancement in Early Jurassic shales due to their swelling and shrinkage behavior

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ABSTRACT

The presence of water in mudrocks has a largely negative impact on production of gas stored in these rocks, due to the fact that water causes swelling of the rock. Removing the water from the mudrock could potentially shrink the rock and increase the overall permeability of the rock. Investigation of the swelling/shrinkage behaviour of the rock during exposure to water vapour is of key importance in designing and optimizing unconventional production strategies. We have used outcrop samples of the Whitby Mudstone and the Posidonia shale, potential unconventional sources for gas in North-western Europe, to measure the swelling and shrinkage behaviour. Swelling and shrinkage of the rocks when exposed to water vapour was measured directly using 1 mm sample cubes in two different setups. The mm cubes were exposed to different levels of relative humidity either in an Environmental Scanning Electron Microscope (ESEM) or in a 3D dilatometer. Swelling of Whitby Mudstone and Posidonia shale is heterogeneous with 2–3 times more measured swelling strain perpendicular to the bedding. Volumetric swelling strains showed values between 0.6 and 2.2% for the Whitby mudstone and the Posidonia shale, respectively. The results suggest that it might be possible to increase permeability in the reservoir by decreasing the in-situ water activity due to shrinkage of the matrix.

1. Introduction

Due to their affinity for water clay minerals play an important role in the safety and economics of many industrial applications. For instance, shrinkage and swelling of clays determine the stability of soils and building foundations (e.g.: Abdullah et al., 1999; Das et al., 2010; Carrier et al., 2013; Erzin and Gunes, 2013), swelling of clays has important implications for drilling operations as it can cause wellbore instability (e.g.: Anderson et al., 2010). Contrastingly, clay swelling could be beneficial to seal off radioactive waste from the environment (e.g.: Delage et al., 2010). The impact of the swelling clays varies and depends on the mineralogy and the texture of the rock, hence the type of clay minerals present and their distribution within the rock (Abdullah et al., 1999; Aksu et al., 2015). The composition of the fluids present also plays a role, where the clay-water-electrolyte system is the main parameter affecting swelling (Abdullah et al., 1999; Aksu et al., 2015). During the drilling of oil and gas wells fluids are used. When water based drilling fluids are employed clay swelling can have a largely negative impact (e.g.: hole closure, casing problems, accumulation of drilled cuttings) on the drilling process significantly increasing well construction costs (Anderson et al., 2010). Due to the presence of swelling clays in the rock texture and/or due to the presence of mobilized clay particles in water-saturated rocks permeability of the reservoir is reduced (Aksu et al., 2015). The sorption induced swelling effects directly influence the opening and closure of pores and fractures in the rocks and influence the permeability, hence the productivity of reservoirs. Investigating the swelling/shrinkage behavior of the rock during exposure to water is of key importance in designing and optimizing unconventional production strategies. Removing the water from the mudrock could potentially shrink the rock and increase the matrix permeability (e.g. for coal: Fry et al., 2009; Liu et al., 2016a). Most studies of clay swelling have been focused on smectites due to their large swelling potential, where techniques have either investigated macroscopic properties such as the bulk volume change (de Jong et al., 2014) or the microscopic properties such as interlayer spacing (using for instance X-ray diffraction; Anderson et al., 2010; Carrier et al., 2013).

We are interested in the swelling and shrinkage of the naturally occurring mudstones the Posidonia shale and Whitby Mudstone (Houben et al., 2016a, 2016b). The Posidonia shale is a possible unconventional source for gas in the Netherlands (e.g.: Herber and de Jager, 2010; Van Bergen et al., 2013; Ter Heege et al., 2015) and the Whitby Mudstone is its time equivalent deposited in the UK in the same basin at the same time (e.g.: Powell, 2010). The Posidonia Shale and Whitby Mudstone are Toarcian age black shales occurring in the UK, France, the Netherlands, Germany and Luxemburg (e.g.: Littke et al., 1991; Hesselbo et al., 2000), and were deposited in an epicontinental sea at variable energetic conditions and periodic benthic oxygen

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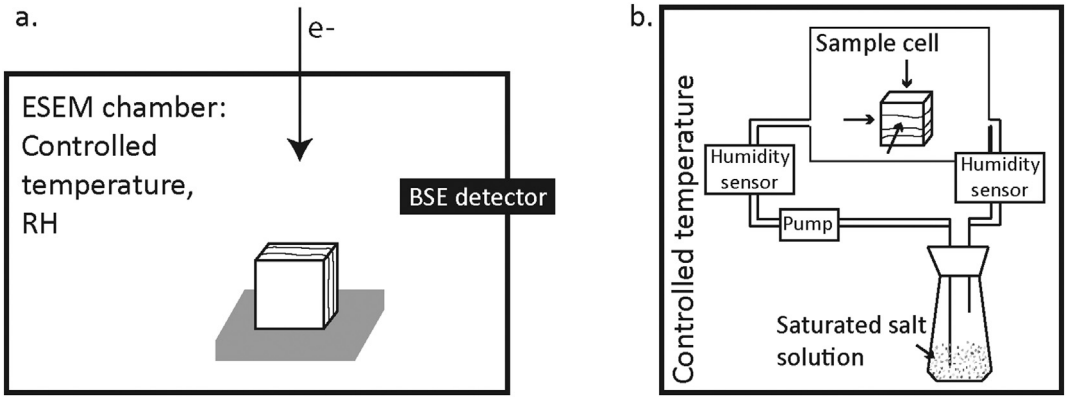

Fig. 1. a. Schematic drawing of a 1 mm cube sample in the ESEM chamber, where the area imaged was polished with a PIPS, and the area was imaged perpendicular to the bedding. b. Schematic drawing of the 3D dilatometer experimental set-up.

depletions (Trabucho-Alexandre et al., 2012; French et al., 2014). Mineral composition of the Posidonia Shale/Whitby Mudstone differs with location and height of the sample within the section (Houben et al., 2016a, 2016b). Organic matter content averges between 8 and 17%, Silicate content ranges between 15 and 25%, Carbonate content varies between 3 and 70% and sheetsilicate content varies between 25 and 85% (Chesapeake, 2010; Powell, 2010; Hilger, 2003; Klaver et al., 2012, 2016; Kanitpanyacharoen et al., 2012; Gasparik et al., 2014; Ghanizadeh et al., 2014; Rexer et al., 2014; Mathia et al., 2016; Houben et al., 2016a, 2016b; Douma et al., 2017). The carbonate and sheetsilicate content are highly variable per sample, whereas the silicate content is more constant and about 20% on average. The sheetsilicates seem to be mostly illite and interlayered illite/smectite, some kaolinite and minor amounts of chlorite (Houben et al., 2016b). The smectite is interlayered with illite in a ratio 80/20, meaning that smectite accounts for approximately 3% of the total mineralogy (Houben et al., 2016b) in the rocks. In the research presented here we have measured the amount of swelling and shrinkage of the Whitby Mudstone when exposed to different levels of relative humidity in 2D using an Environmental Scanning Electron Microscope (ESEM), in combination with measuring the volumetric change of a 1 mm cube of Whitby mudstone and Posidonia shale when exposed to different levels of relative humidity using a 3D dilatometer (Liu et al., 2016a).

2. Materials

2.1. Posidonia shale and Whitby mudstone samples

Samples used were Posidonia shale (Dotternhausen; PSFD) and Whitby Mudstone (Jet rock section; WMF) samples (Houben et al., 2016b). All investigated samples were outcrop samples collected during fieldwork (Posidonia shale - Dotternhausen, Germany; Whitby mudstone - Runswick Bay/Port Mulgrave, United Kingdom). Subsamples of 1 mm sized cubes were prepared in the Glass Workshop at Utrecht University, using a high precision digitally controlled diamond wafering saw, cooled by air. Many cubes were prepared simultaneously by first sawing a 1 mm thick wafer of clay which was afterwards sawed into cubes. The wafer was prepared parallel to the bedding meaning that the cubes were prepared from the same sample bed. The 1 mm cubes were dried at 50 °C in an oven prior to the experiments for at least 24 h, so that all samples investigated had a similar starting humidity.

3. Methods

3.1. ESEM

Ten 1 mm cubes were glued onto a Scanning Electron Microscope (SEM) stub using a carbon sticker so that the top sides of the cubes were oriented perpendicular to the bedding. The top side of all cubes were polished simultaneously using a Precision Ion Polishing System (PIPS; Fischione, SEM mill, model 1060). After polishing, a grid of 16 squares was deposited on some of the polished surface using the Pt target in the SEM (Nova Nanolab 600 FIB-SEM; De Winter et al., 2009; Liu et al., 2016b). The deposited squares were about 20 × 20 µm in size and spaced about 200 µm apart. Five polished cube surfaces were prepared with a grid, and five cube surfaces were polished while no grid was deposited on these surfaces. For all 10 polished top surfaces an SEM mosaic was made using a JEOL Neoscope II JCM-600 SEM. Based on the quality of the final polish three cubes were selected for investigation with an Environmental SEM (ESEM; Philips XL30 ESEM). All samples originated from the WMF4 sample block featuring a mineralogy of; 51.3% of sheetsilicates, 13.1% of silicates, 26.1% of carbonates, 0.8% of oxides, 7.7% of sulphides and 0.9% of sulfates (Houben et al., 2016a). The single sample cubes were exposed to different saturated vapour pressures at 0.5 °C inside the ESEM chamber so that the samples were exposed to a relative humidity varying between 0% and 100% depending on the pressure in the chamber (e.g.: Stokes, 2006). Fig. 1a shows for the experimental setup. By changing the vapour pressure in the ESEM chamber the relative humidity in the chamber changed. As soon as the pressure was stable the relative humidity in the chamber was stabilized as well. Pictures of the sample were always taken after the relative humidity in the ESEM chamber stabilized. Two of the sample cubes investigated (WMF4 Block 1 and WMF4 Block 2) had a Pt grid deposited on the top surface. Both sample cubes were firstly exposed to a relative humidity of 0% and after a calibration time of circa 1 h a picture of the whole polished surface was taken using a Back Scattered Electron (BSE) detector at a magnification of 100× (pixel size = 0.9 µm). Where after the pressure was increased enabling the relative humidity of the ESEM chamber to rise to 50%. After a calibration time of about 10 min exposing the sample to the new relative humid atmosphere the sample was imaged again with the BSE detector using a magnification of 100×. Next step was to increase the pressure in the ESEM chamber even more so that the relative humidity of the atmosphere in the ESEM chamber rose to 100%, and the sample was equilibrated for about 10 min in this atmosphere where after the sample was imaged again using the BSE detector at a magnification of 100×. After the relative humidity of the atmosphere had been increased to 100% it was decreased for WMF4 Block 1 to 0% and the samples was imaged again to compare the before and after dimensions of the sample. For WMF 4 Block 2 the relative humidity of the chamber was only increased from 0 to 100% and not decreased after. One other sample without Pt deposited grid (WMF Block 3) was used for swelling/shrinkage experiments, this samples was firstly exposed to a relative humidity of 0% in the ESEM chamber where after the relative humidity of the ESEM chamber was stepwise increased to 50% and to 100%. After the relative humidity had been up to 100% the humidity of the