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Matrix to Fracture Flow Inferences from Core Measurements and Structural Fabric (Whitby UK)

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SUMMARY

The Early Jurassic (Toarcian) Shales in Northern Europe are investigated as possible unconventional sources for gas, where gas in shales is trapped in poorly connected micro pores and is sorbed within particles of organic material and clay minerals in the matrix of the host rock. Having a dual permeable medium consisting of a high permeable fracture network together with a tight shale matrix will improve gas flow rates from matrix to well. The Whitby Mudstone is currently outcropping on the Yorkshire coast hence getting sufficient sample material for permeability experiments is easily available, in combination with mapping of the natural occurring fractures in the cliffs and pavements along the coast this area is an ideal natural analogue to investigate matrix characteristics in combination with the natural fracture network. The studies show that fracture spacing on average is in the order of 10 centimeters and that in combination with a matrix permeability of 1·10-18 m2 results in gas residue times in the matrix in the order of hours to tens of days depending on the input parameters used.

Introduction

New possible gas resources are needed to prolong the gas production capacity of the Netherlands. The use of gas will help to reduce the use of coal for energy production and in that respect decreases carbon dioxide emissions. The Early Jurassic (Toarcian) Shales in Northern Europe are investigated as possible unconventional sources for gas, where gas in shales is trapped in poorly connected micro pores and is sorbed within particles of organic material and clay minerals in the matrix of the host rock. To extract the gas from the rocks, a fracture network is often required that can act as a flow path for fast transport from reservoir to well. A dense network of fractures can substantially increase the permeability of the rock and in addition to induced fractures connected to the production well the existence of open natural fractures can augment the effective permeability of the tight shale matrix.

Here we have investigated the natural fracture network, matrix permeability, and possible pathways for the gas through the Whitby Mudstone. Our research focusses on the Whitby Mudstone because it is the UK time equivalent of the Posidonia Shale, the main hydrocarbon source rock in the North Sea (Herber and de Jager, 2010). The Whitby Mudstone is currently outcropping on the Yorkshire coast hence getting sufficient sample material for experiments is relatively easy, in combination with mapping of the natural occurring fractures on the cliff and pavement along the coast this area is ideal to investigate matrix properties of the rock in combination with natural fracture spacing.

Measured matrix permeabilities for the Whitby Mudstone are in the order of Micro to Nano Darcy and typical microstructures reveal no obvious pathways for the gas at the resolution used for imaging, meaning that connections between single pores have throats below 100 nm in diameter. The natural fracture network in the pavements along the coast (Port Mulgrave, UK) show a connected network with the longest fractures in the N-S direction. Average spacing of matrix blocks to the nearest, often small, fracture are in the order of 0.1 meter. The directions shows a strong directional variance as the E-W average distance is 0.07 meter whereas in the N-S directions this is 0.13 meter.

Methods

Sample selection - Whitby Mudstone samples were collected at the Yorkshire (UK) coast close to the villages Runswick Bay and Port Mulgrave (Houben *et al*., 2014; Houben *et al*., 2016). Sample material originates from the organic matter rich part of the Whitby Mudstone, the bottom eight meters of the Mulgrave Shale member (Houben *et al*., 2016).

Microstructural imaging - A combination of Ar ion beam polishing (PIPS) and Scanning Electron Microscopy (SEM) has been used to image both microstructure and porosity in selected Whitby Mudstone samples. Maximum sample diameter was 8 mm and samples have been prepared and Ar ion beam polished perpendicular to the bedding (Houben *et al*., 2014; Houben *et al*., 2016).

Matrix permeability measurements - An Ar-gas permeametry set-up has been used to measure the Ar-gas permeability of WMF samples, making use of the pressure transient step decay method (Rocksalt - Sutherland & Cave, 1980; Peach & Spiers, 1996; Clay – Cui *et al*., 2009; Zhang *et al*., 2013). The samples used were 1 inch diameter cores, cored perpendicular to the bedding and sample length varied between 1.7-2.7 cm. The sample to be measured was placed in between two plastic stems and jacketed in a rubber sleeve sealed to the stems. This set-up was pressurized with a jacket pressure (Pj) to prevent a blow-out. The Ar-gas permeametry set-up exists of an upstream gas reservoir of a known volume; V1, the sample and sample holder, and a downstream reservoir of a known volume; V2.
All volumes (V1, V2, sample) were evacuated for at least one hour before the experiment started to ensure the system only contained Ar gas during the measurements. The jacket pressure and the pressure in Volumes 1 and 2 was increased to the desired values so that an effective confining pressure of 0.8 MPa was reached. The system was left for equilibration for at least one hour enabling the Ar gas to enter the sample. The upstream (V1) and downstream (V2) volumes were disconnected by means of valves and the Ar gas pressure in V2 was decreased to 0.2 MPa lower than the pressure in V1. The exact pressure and temperature at both sides of the sample was measured every 5 seconds, monitoring the amount of time needed for the pressure to equalize by penetrating through the sample.

Pressure equilibrium depends on the sample material, jacked pressure, kind of gas that has been used for the flow through and pressures in V1 and V2. After a run was finished the raw data was used to calculate the corresponding permeability value.

Fracture network imaging - Natural fracture networks present in the outcrops along the UK coast near Port Mulgrave were imaged from ca. 2 m height using a photo camera attached to a stick. A grid on top of the pavements was used to know the geographical location (UTM GPS coordinates) of all grid points and the direct distance between the grid points acted as a second measure for knowing the relative distance between the different photos. For the overlap ca. 10 pictures per 5 meters were taken and these were used to create a high resolution 2D map (cm resolution) of the pavement and the fractures therein of areas covering about 10 by 10 meters. In ArcMap these pictures could then be used to digitize all fractures visible in the images.

Results

Microstructures - The microstructures found in the Jet rock section of the Whitby Mudstone can be subdivided into a carbonate fossil rich upper 3 meters and a sub mm-scale laminated bottom 4 meters where layers with <1% organic matter are interchanged with layers that show organic matter contents up to >10% (Houben *et al*., 2016). Most abundant pores are pores within the matrix, but this porosity is unconnected at the resolution used for SEM imaging (pixel size circa 25 nm).

Permeability - Permeability measurements were performed on five Whitby Mudstone samples taken throughout the circa eight meter high Jet rock section (from top to bottom sample numbers: 4, 6, 15, 1 and 23). Experiments were performed at an effective confining pressure of 0.8 MPa and at different mean gas pressures to correct for the gas slippage effect (Klinkenberg, 1941). The experiments performed on the different cores all show a decreasing permeability with increasing mean pressure, meaning that the permeability measured should be corrected for the Klinkenberg effect (e.g.: Klinkenberg, 1941; Wu *et al*., 1998; Tanikawa & Shimamoto, 2006). The Klinkenberg corrected measured permeability values measured are on average $1 \cdot 10^{-18}$ m^2 (1 μDarcy). So far a mineralogy - permeability relation was not found, the carbonate rich samples from the upper half Jet rock show permeability values that are similar to the permeability values found in samples originating from the lower half of the Jet rock section.

Fracture network - The fractures in the Jet rock section of the Whitby Mudstone are visible in both the pavement as well as in the cliff (Figure 1). The largest and widest spaced fractures in both the cliff and the pavement are mainly oriented N-S. Smaller fractures show dominant N-S and E-W orientations. An orthogonal fracture network geometry was found in all investigated areas, that is fully connect in 2D in the horizontal plane (pavement) whereas in the vertical plane (cliff) fractures are not connected.

Figure 1 *Pictures of the fractures in the pavement and cliff at the coast near Pore Mulgrave (UK).*

Both fracture length and spacing are directional dependent. Fractures in the pavements are on average closest spaced in the E-W direction (on average: 0.07 m E-W and 0.13m N-S). This is reflected by the fractures visible in the cliff, showing more and closer spaced fractures in the E-W direction although N-S fractures are usually longer and run more often through the entire seven meter thick Jet rock section. Most fractures in both E-W and N-S sets seem to terminate in the middle of the Jet rock section around the large (up to 80 cm diameter) carbonate nodules dominantly dividing the Jet rock in a lower and upper half (Whale stones).

Conclusions

A first attempt to upscale the permeability data measured on cm-sized samples to the m-scale, and prediction on travel times needed for gas to travel from the matrix into the fracture network can be made by combining the permeability examination of the matrix (below dm scale) with the natural fracture arrangement at the meter scale. The cliffs do not show a connected fracture network but in the horizontal plane all fractures show cross-connectivity and a dense fracture network with average fracture spacing in the orders of tens of centimeters has been found. This implies that when we assume that this fracture network is present at a depth of 3 km's, the fractures are open and under hydrostatic pressure, the overpressure in the matrix is in the order of 10% and the matrix permeability is $1 \cdot 10^{-18}$ m^2, than it takes about 2.5 hours for a gas molecule to travel 0.1m and circa 11 days to travel 1 meter.

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