THIN SECTION IMAGE ANALYSIS FOR ESTIMATION OF INITIAL WATER SATURATION IN SILICICLASTIC RESERVOIR ROCKS

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ABSTRACT

One of the parameters needed for determination of (initial) water saturation is the knowledge of irreducible water saturation (S_{wirr}). It is also essential for multiphase flow behavior, e.g., as an endpoint for relative permeability curves. Estimations of S_{wirr} is most commonly from capillary pressure laboratory experiments, however this is time consuming and resource intensive, which results in a limited number of core plugs being investigated for a given reservoir. For these reasons alternative methods for estimation of S_{wirr} is desirable. In this paper we estimate S_{wirr} from analyzing backscatter electron (BSE) images of thin sections of reservoir rocks. We argue that the irreducible water saturation is closely linked to the smallest pores in the reservoir rock, typically related to authigenic clays. The amount of such pores is estimated from the BSE images. Our results give a good match with results from more traditional laboratory experiments. The technique is thus a fast, cost efficient and reliable way to estimate S_{wirr} of siliciclastic reservoir rocks.

INTRODUCTION

Initial water saturation (S_{wi}) is one of the most important parameters for determining oil and gas in place in a reservoir. For most of conventional sandstone reservoirs at initial condition, the S_{wi} above the transition zone is approximately given by S_{wirr}. For rock samples S_{wirr} is commonly determined by laboratory techniques such as porous plate or centrifuge. The number of investigated core plugs is thus limited due to time and cost issues. Since S_{wirr} is commonly used to calibrate water saturation models, calibration is then based on a restricted number of core plugs. Additionally, these core plugs are often chosen for special core analysis and are selected for their homogeneity and do not represent properly the entire collection of rock types. Water saturation can also be obtained directly from logs (NMR) but they are only estimates if no calibration is made.

Thin sections are routinely taken on drilled core plugs (trimmed ends). In this paper we introduce an alternative method for estimating S_{wirr} from analyzing BSE images of thin sections of reservoir rocks. From the BSE images, it is possible to quantify porosity, solid fraction (mainly quartz) and micro porous phase such as authigenic clay. In the Norwegian continental shelf, most of the reservoir rocks are sandstones containing clay (mainly illite, smectite and kaolinite). As clay is linked to the smallest pores in the reservoir rock [1], the amount of clay can be directly correlated to S_{wirr}.

Our results give a good match with results from more traditional laboratory experiments. The technique is thus a fast, cost efficient and reliable way to estimate S_{wirr}.

This study is based on a selection of 52 core plugs all originating from the same field in the Norwegian continental shelf. Core plugs were selected to capture the porosity and permeability range and observed rock types in the reservoir. Porosity and permeability for our samples range from 0.20 to 0.31 and from 0.1mD to 6D respectively, while the clay content range from 5.4% to 36.2%.

METHODOLOGY

Irreducible water saturation

The capillary pressure P_c needed for entering a circular pore is given by the Young-Laplace equation:

$$P_c = \frac{2\sigma . cos\theta}{r} \qquad (1)$$

where σ is the interfacial tension, θ is the contact angle, and r is the radius of the pore and pore throat. For a homogeneous fluid the interfacial tension and contact angle is assumed constant, hence the capillary pressure is inversely proportional to the pore radius.

Consider a rock sample initially filled with water where we start injecting oil (or gas) replacing the water. The oil will first invade the largest pores, since entering them takes the smallest capillary pressure. While gradually increasing the capillary pressure, the oil will enter smaller and smaller pores as foretold by the Young-Laplace equation. A capillary pressure curve for a typical reservoir rock is given in Figure 1. The height above the free water level for typical fluid densities is also included. We see that the curve seems to reach a kind of asymptote around a water saturation of 20%, which is interpreted as S_{wirr}. However capillary pressure curves do not always display an asymptote, so S_{wirr} is not well defined.

Values for S_{wirr} are usually obtained from different laboratory techniques, e.g. porous plate and centrifuge; however these techniques will not be described in this paper.

Authigenic clay in siliciclastic rocks

There typically exists different clay type dispersed in the pore space of reservoir sandstones, as shown in Figure 2. This authigenic clay is between sand grains, and is not strongly affected by overburden pressure. Also evident in Figure 2 is porosity inside the clay, called microporosity, with a typical pore size in the range of 100Å to 1000Å [2]. Using the Young-Laplace equation, Eq.1, with interfacial tension σ =30 mN/m and θ=30 degrees then yields capillary pressures in the range of 2.6 to 26 bar. To reach such capillary pressures in the reservoir one needs a significant oil column (over 100m for typical water oil system with density of 1000 and 800 kg.m^{-3} for water and oil respectively), therefore the microporosity in the clay is assumed to be water filled.

From [2], kaolinite has microporosity varying from 25 to 50%. Chlorite has a generally uniform grain-coating texture and microporosity of about 50%. Illite has higher microporosity value between 50 and 70%. Microporosity associated to clay then varies from 30% to 70%. Thus microporosity can be adjusted according to the main clay type present in the investigated sample.

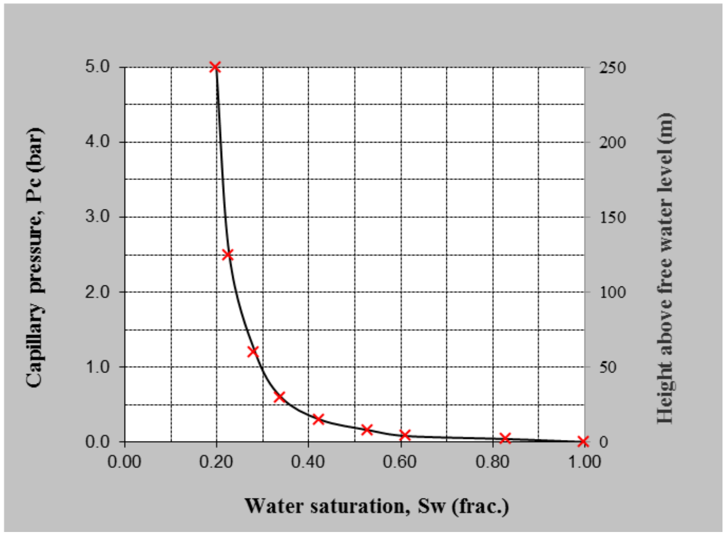

Figure 1: A capillary pressure curve for a typical reservoir rock. The plot shows the capillary pressure at different water saturation for a primary drainage of water by oil. The height above the free water level for typical fluid densities is also included.

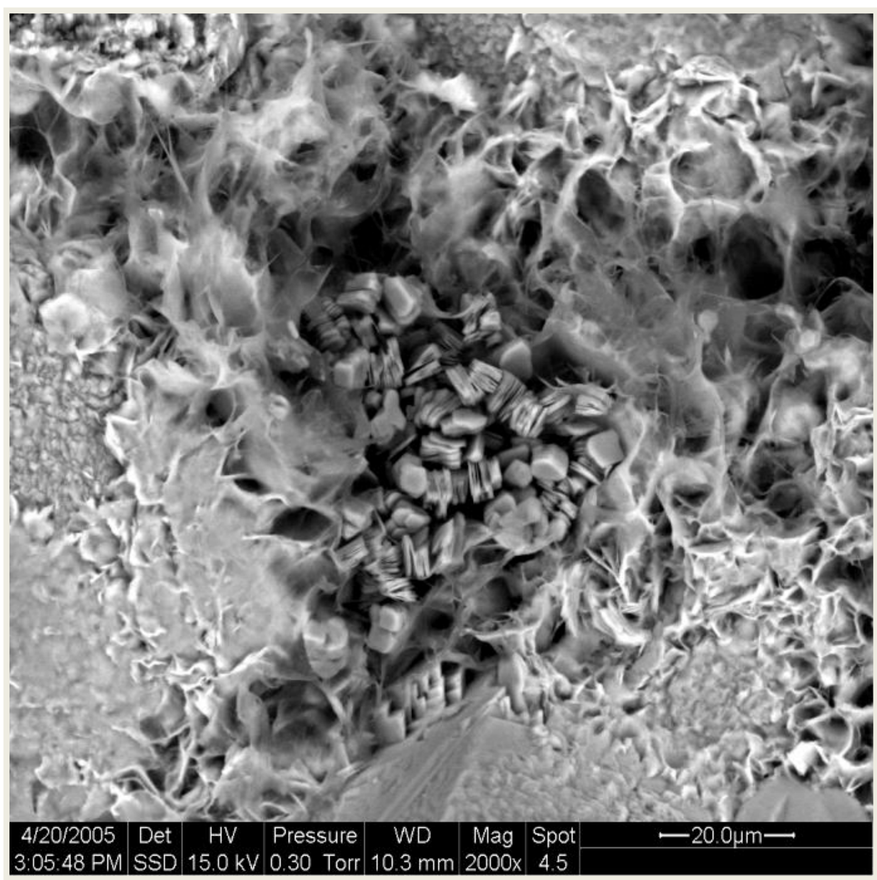

Figure 2: BSE image showing clay in between the sand grains in a reservoir rock. The center of the image shows pore filling kaolinite, while both pore bridging and pore lining clay can be seen in other parts of the image.

Thin section imaging and image analysis

Thin sections were made from trimmed ends of drilled core plugs. The thin sections were 25 micron thick with a color-impregnated pore system, polished surface, and no cover glass. BSE images were taken with a FEI Quanta SEM with a Bruker Quantax EDS system at different pixel resolutions from 0.5μm to 3.5μm. In order to capture possible heterogeneities, BSE image mosaics of the whole thin section were automatically made (Figure 3). All image analysis was conducted on these mosaics. The segmentation process is performed semi-automatically. The whole process takes approximately one to two hours per thin section mosaic. In the BSE image of a thin section, parts of the porosity are resolved as shown in Figure 3. Following [1] the resolved porosity is called *image porosity* and denoted $\emptyset_i$. The unresolved porosity is denoted by $\emptyset_\mu$.

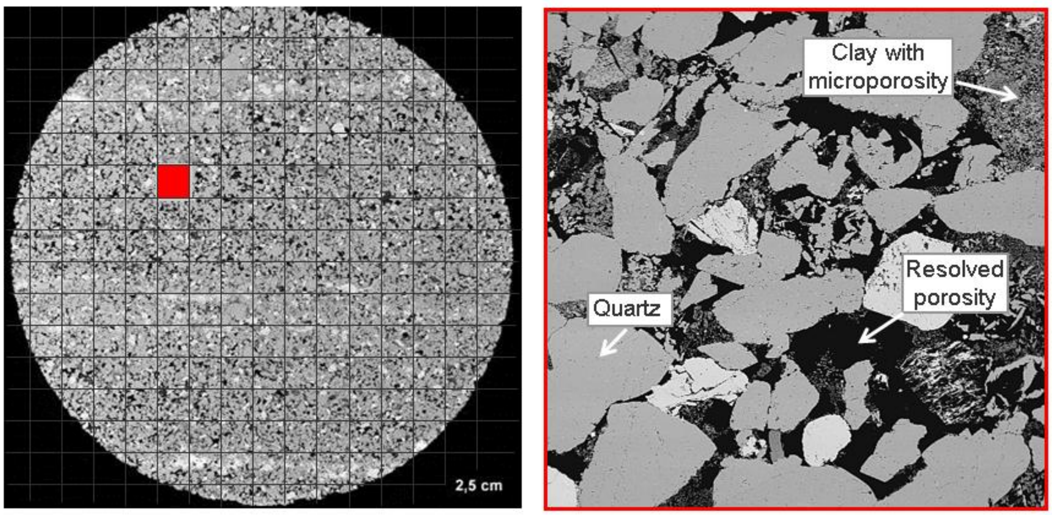

Figure 3: Mosaic of BSE images from a 2.5 cm thin section of NCS sandstone on the left, together with an individual BSE image on the right.

The grey-levels in the BSE image between the levels for resolved pores and the levels for quartz are associated with clay, and the fraction of such pixels is denoted V_{clay}. The main clay types observed in the different thin sections are chlorite, smectite, kaolinite and illite. As noted above, clay has associated microporosity, hence the unresolved porosity is partly microporosity in clays. Also rock fragments and borders between grains and pores might yield grey levels now associated with clay, hence the amount of clay can be overestimated. For each image the unresolved porosity was estimated using the following formula:

$$\emptyset_\mu = \frac{V_{clay}\mu_{clay}}{V_{tot}} \qquad (2)$$

where μ_{clay} is the microporosity associated to the unresolved voxels and V_{tot} is the total amount of pixels. Total image porosity is then obtained by summing the different porosities as:

$$\emptyset_{\boldsymbol{t}} = \emptyset_{\boldsymbol{i}} + \emptyset_{\boldsymbol{\mu}} \qquad (3)$$

Based on clay types (mainly kaolinite) and to minimize the difference between total image porosity and plug porosity we used $\mu_{clay} = 40\%$ as microporosity for all samples. The resulting calculated total image porosity $\emptyset_t$ versus helium porosity for the 52 plugs where the thin sections are taken are shown in Figure 4. The clustering around the 1-1 line gives confidence in the value used for microporosity μ_{clay}.

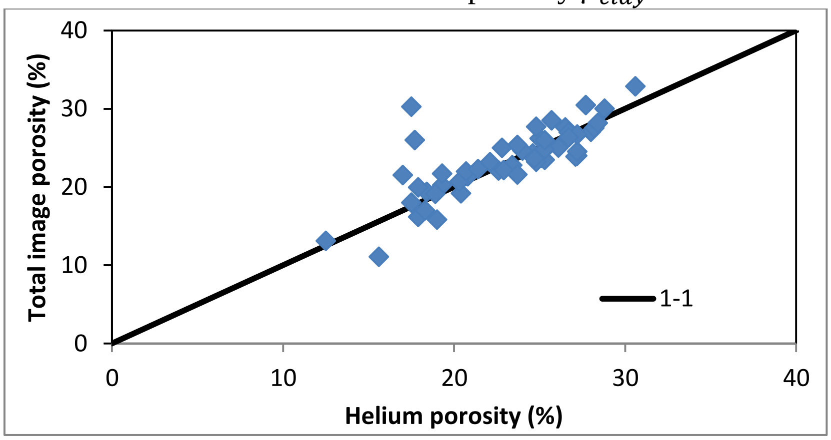

Figure 4: Helium porosity for the investigated plugs where the thin sections are taken from vs. the calculated total image porosity using 40% micro porosity.

RESULTS & DISCUSSION

Estimation of S_{wirr} from image analysis

As mentioned before, the pores in the clay are so small that oil will not enter them for typical capillary forces in the reservoir. Thus the microporosity in the clay will contribute to S_{wirr}. At S_{wirr} there will also be water present e.g. in corners in the pore space and between rock fragments with pore sizes in the same range as the clay. However, since both rock fragments and borders between grains and pores gives grey levels associated with pores, the water present corners in the pore space and between rock fragments is already accounted for by the over-prediction of clay. However, for sandstones with significant amount of clay the clay bound water will dominate S_{wirr}. We can then estimate S_{wirr} using the following formula:

$$S_{wirr} = \frac{\emptyset_\mu}{\emptyset_t} \qquad (4)$$

In Figure 5 we have plotted S_{wirr} calculated using Equation (4) versus permeability measured on the plug from where the thin section is taken. We have also plotted available experimental data from the same field and same wells. All experiments were performed using a porous plate method with a maximum end pressure of 5 bars. The values for S_{wirr} from image analysis give a similar trend line as laboratory experiments, also seen in Figure 5. This gives confidence in the calculated S_{wirr} values. Since clay is filling and blocking pores, the correspondence between S_{wirr} and permeability is as expected, and is well known [1, 3]. The investigated samples have clay content from 6% to 36%. The clay types present is these samples are kaolinite (mainly), smectite, illite and chlorite. For this range of clay content the results obtained are satisfactory and are not deviating from observed experimental data.

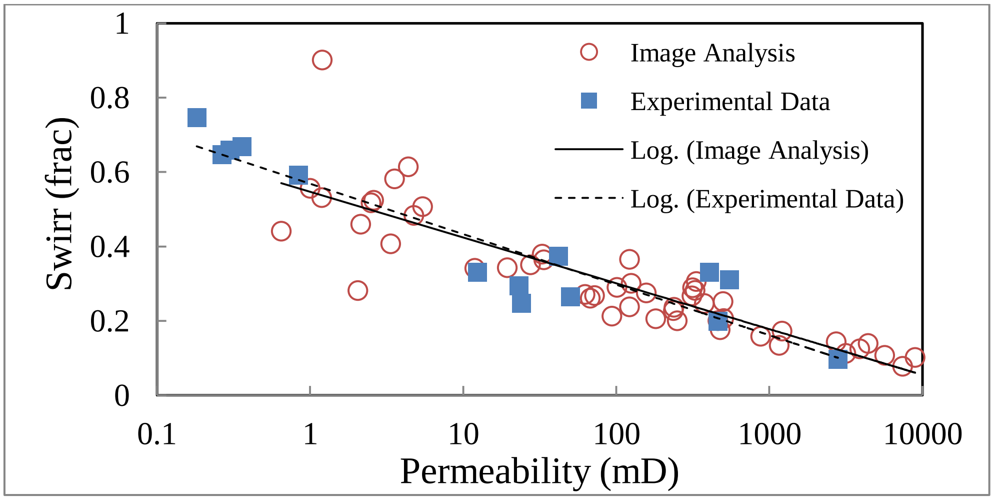

Figure 5: Permeability versus irreducible water saturation (S_{wirr}) for the BSE images and core plugs from a NCS reservoir.

CONCLUSION

In this paper we describe a method for estimating S_{wirr} directly from image analysis of thin sections. For the Norwegian continental shelf the microporosity associated to clay varies from 30% to 70% according to the clay type. Using a microporosity value of 40% gave a satisfactory match to experimental data for the samples used in this study. The capillary pressures needed for oil to invade the pores (mostly clay) not resolved in the BSE images are commonly higher than what is reached in the oil column of a typical reservoir. The assumption that this unresolved porosity is only water filled is sufficient to have a good estimation of S_{wirr} for the broad range of siliciclastic reservoir rocks investigated in this study.

Commonly only a limited number of experimental data is available, especially in early phase of field development. Applying the technique described in this paper allows for extending the dataset drastically.

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