BENEFIT OF COMPLEMENTARY METHODS FOR CHARACTERIZING SANDSTONE CORES

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ABSTRACT:

This Paper is based on detailed mineralogical, structural, petrophysical and geochemical studies of sandstone core samples, using routine methods. These include Magnetic Resonance Imaging (MRI), Nuclear Magnetic Resonance (NMR), X-ray Computer Tomography (CT) Scanning, particle size analysis, point counting based on petrographic thin sections, Environmental Scanning Microscopy (ESEM), X-Ray Diffraction (XRD), and X-Ray Fluorescence (XRF). In this study we demonstrate the feasibility of combing these complementary methods of measurements in the characterization of sandstone cores. Four types of sandstones (Slick Rock Aeolian, Fife, Locharbriggs and Berea sandstones) that differ in grain size, porosity and mineralogy have been characterized. The results of the different methods used were found to be consistent with each other, but the combination of a variety of methods has allowed a more complete characterization of the rock samples than each method used on its own. This study has shown that rock heterogeneity at the sub-cm scale may have a significant effect on reservoir petrophysical characterization.

INTRODUCTION

The need for accurate reservoir characterization is important in developing an understanding of geologic complexity that impacts field development. Reservoir quality, primarily determined by the porosity and permeability of the relevant formations, is controlled by many parameters. These include the nature of the constituent minerals and cement, the degree of rock cementation; the degree of sorting or equivalently the particle size distribution of the grains; and the pore-size distribution (Cade et al., 1994). Field development methods that rely on core flooding are particularly sensitive to small-scale changes in reservoir quality. Meanwhile, most waterfloods in sandstone cores are carried out either in almost homogeneous samples or else in core samples of uncertain heterogeneity. Several experimental techniques exist to identify, characterize and take into account the small scale heterogeneity in SCAL program. It is current practice to combine CT-scanner, NMR, Tracer tests, and Hg porosimetry to select the best appropriate samples. Even with a certain degree of heterogeneity, dedicated interpretation techniques based on the fluctuations observed on the repeated saturation profiles as a function of time during the core flooding enable to account for the heterogeneity in the final results (Egermann and Lenormand, 2005). Arns et al. (2001) have shown that direct calculations on high-resolution X-ray computed microtomography images of Fontainebleau sandstone produce permeability and conductivity values which are in very good agreement with laboratory measurements. Ioannidis et al. (1996) have analyzed back-scatter SEM images of cross-sections of several porous rocks in order to determine the statistical properties of the porous microstructure. This study has the aim to demonstrate that by using a suite of techniques in combination; subtle variations in petrophysical characteristics emerge that adds significant value towards a better description of reservoir properties.

METHODS OF MEASUREMENTS AND RESULTS

The materials chosen for the study were Fife and Locharbriggs sandstones - both from southwest Scotland, Slick Rock Aeolian sandstone from Utah, United States and Berea sandstone from Ohio, United States. The four different type of sandstone used in this study present very variable microstructural properties. The preliminary MRI measurements performed on sample 8 of the Slick Rock Aeolian sandstone showed that no images were obtainable using the conventional MRI at 4.7T, because the transverse relaxation T2* was reduced dramatically by the presence of iron. The transverse relaxation T2* used for this experiment was equal to 100us. In general, a transverse relaxation T2* of 10ms or greater is necessary for conventional MRI. We have repeated the experiment using a lower magnetic field of 1.5T unfortunately it was not possible to obtain any image. The reason is the heterogeneity of local magnetic susceptibility. We conclude that the Slick Rock Aeolian samples could not be characterized by NMR at high field or at low fields due to total iron content and to its large spatial heterogeneity. As a consequence, the continuous-wave magnetic resonance imaging (CW-MRI) technique was used for the visualization of the sample (Baraka-Lokmane et al., 2001). The results using the continuous-wave magnetic resonance imaging (CW-MRI) technique clearly show the development of water front (Fig.1). X-ray Computer Tomography (CT) scanning images (Fig.2) show the different mineral phases: calcite in white, microcline in light grey, and quartz in dark grey. The white areas seen on the images indicate the presence of calcite cements (Figs 2a and 2d). The iron banding is seen in the near-white and white layers (Figs 2a and 2b). The XRD, XRF analyses and the petrographical study have shown that the highly attenuating mineral contains iron. For the Berea sandstone samples, the different CT images have shown a very homogeneous and isotropic material. Figure 2c shows the presence of white areas, indicating the development of nodules, which could be calcite or iron. We conclude that the method is particularly useful for imaging calcite and hematite or iron. Our 3-D ESEM measurements have enabled the direct measurement of the wettability of the different minerals, and the identification of the mineralogy of the samples. This study showed that fresh surfaces of quartz and feldspar are both water wet (Figs 3 and 4). Interstitial illite particles or quartz and feldspar minerals covered by clay particles (illite, kaolinite, and smectite) are all very water wet (Figs 5 and 6). The Slick Rock Aeolian sandstones present the lowest porosity (21.6%). For the Locharbriggs, Fife and Berea sandstones the porosity is in the range of 22.5 %, 24.4% and 24.3% respectively. The Fife sandstones are the most homogeneous; the main detrital components are represented by quartz with an amount of 83%. These samples present the biggest mean grain size (varying between 294.1 μm and 368.4 μm). They present the lowest percentage of cement, varying between 4.7% and 6.3% constituted mainly by kaolinite; with these microstrutural characterizations, we expect the highest values of permeability for these samples. Indeed the permeability measurements showed that the Fife sandstones have the highest liquid permeability, 1980.50mD±388.20 and gas permeability equal to 1366.50mD±62.93. The Slick Rock Aeolian sandstones present the lowest porosity (21.6%). The cement varies between 5.5% and 13.5%; it is in the form of clay minerals (mainly illite) varying between 4% and 8%. The Locharbriggs sandstone samples present the smallest mean grain size (varying between 193.7 μm and 206.1 μm) and a relatively high percentage of cement (5.7% and 10.2%), mainly in the form of clay minerals (illite, kaolinite and smectite). These swelling clays reduced the water permeability. Berea sandstone presents porosity in the range of 24.3%. The cement (around 18 %) is represented by clay minerals (illite and kaolinite), varying between 9.3% and 10%, calcite (about 8%) and iron. According to these parameters, we expect lower values of permeability compared to the other types of sandstone because of the high level of cement and a relatively high level of clay minerals. In fact the Berea sandstones have the lowest permeability. The liquid permeability is in the range of 172.50mD±3.53, the gas permeability, 306.50mD±12.02.

DISCUSSION

The results of the different methods used were generally found to be consistent with each other, although no individual technique gave the full picture. Each of these methods of measurement has its own particular advantages and disadvantage (Table 1). The finite and heterogeneous nature of iron in the sample is confirmed independently by the CT scans and by the absence of a resolvable signal in the MRI measurements. Likewise, the determination of the mineralogical composition of the samples, the type and the abundance of the cements, and particularly the location and the abundance of the calcite and hematite, are all well characterized by several independent methods. These include the 2-D point counting method, the 3-D (quantitative) XRD analysis and 3-D (qualitative) methods (CT-Scanning images and ESEM measurements). The point counting method has shown that the reddish layers of the samples coincide with the hematite cement, which has a very high density and appears on the CT scanning images with a white color. This explains the problems encountered in the MRI measurements; predominantly due to magnetic susceptibility variations within the sample, which distort the field lines is due to the presence of iron (hematite), especially when it is not homogeneously distributed, as here. The ESEM measurements carried out on the Locharbriggs samples show the presence of smectite cement, which was not detected by the XRD measurements. The ESEM measurements carried out on the Berea sandstone samples have also shown the presence of iron nodules. This indicates the importance of using complementary method of measurements for characterizing a rock sample. The point counting has shown the finite presence of hematite, which was not detected with the XRD measurement because of its small concentration (less than 1% of the sample). This is also the case of the pyrite cement for the Locharbriggs sandstone samples. A structural method (point counting technique) is therefore complementary to a quantitative method (bulk XRD analysis) in order to identify the different mineral species and quantify their abundance. The use of X-ray diffraction (XRD) techniques for quantifying clay content can be very time consuming, requiring significant sample preparation, and generally examine only a relatively small sample volume. Potter et al. (2004) have used magnetic susceptibility for quantifying illite content in sedimentary rocks. The magnetic method is also capable of estimating other minerals in the core samples.

CONCLUSIONS

Although accurate description of complex oil reservoirs requires significant effort on the part of a number of technical disciplines, the systematic analysis of the routine core data is necessary to gain insight into the complexity of permeability distribution and to focus reservoir description effort. Good core coverage and full use of the resulting core data are required to manage complex oil reservoirs. Core scale data can play a vital role in development drilling programs and recovery planning operations. Laboratory testing procedures can strengthen log interpretation criteria, aid in completion/stimulation operations, provide a sound basis for reserves estimates and reservoir modeling, and supply much needed guidance in secondary and tertiary recovery programs. The results of this study conducted on four sandstone cores indicate the added value of combining several techniques. The 3-D X-ray computer tomography technique provides information about the rock heterogeneity, the point counting using thin sections is necessary for obtaining the mineralogy composition of the rock as well as the estimation of the porosity. The XRD measurements will refine the results of the point counting using thin sections by providing the different types of clays. The ESEM measurements are essential for the wettability determination of the different minerals, and the grain size analysis is useful to supplement porosity for empirical permeability estimation.

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Table 1: Benefit of the integrated approach used in this study

Method of measurement	Measured parameters	Comments on the advantages	Comments on the disadvantages
3-D X-ray Computer Tomography	• Rock heterogeneity • Presence of iron and calcite	• Relatively rapid method of measurement • Not destructive method	• Interpretation of the grey scale is challenging • Previous petrography analysis is necessary
3-D MRI	• Structure of the core • Distribution of water inside the core • Fracture geometry	• Powerful tool for qualitative and structural analysis • Not destructive method • CW- MRI: quality of images need to be improved	• Presence of iron • Heterogeneity distribution of iron
3-D ESEM	• Wettability of the different minerals	• Relatively rapid method of measurement	• No disadvantages
3-D SEM/ EDX	• Mineral identification	• Relatively rapid method of measurement	• Qualitative and not quantitative method of measurement
3-D Particle size	• Rock heterogeneity • Mean grain size	• useful to supplement porosity for empirical permeability estimation	• Not always easy to obtain grains from a sandstone core
2-D Point counting using thin sections	• Percentages of the different mineral constituents and porosity • Identification of the dominant cement	• Structural analysis • Identification of rare minerals	• Time consuming
2-D analysis: Imaging software Scion Image	• Porosity estimation	• Relatively rapid method of measurement	• No disadvantages
3-D XRD	• Mineralogy composition	• Quantitative analysis • Independent method from point counting • Identification of the different types of clays	• Minerals present with less than 1 % of the rock are not identified
3-D XRF	• Chemical composition	• Quantitative analysis for most elements with concentrations as low as 1ppm	• time consuming

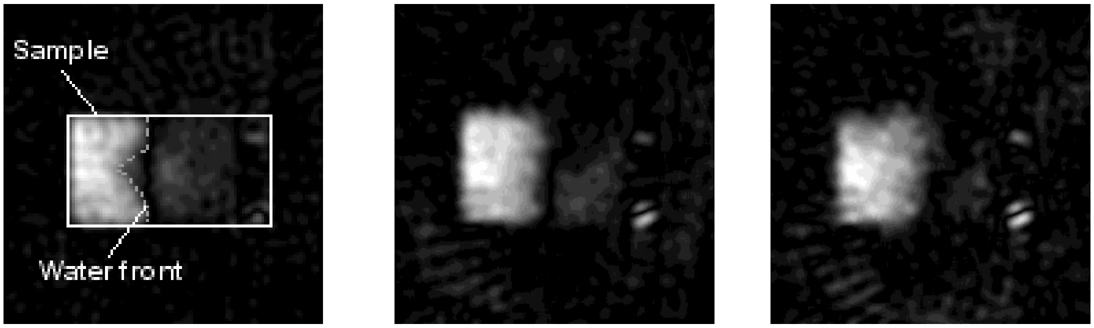

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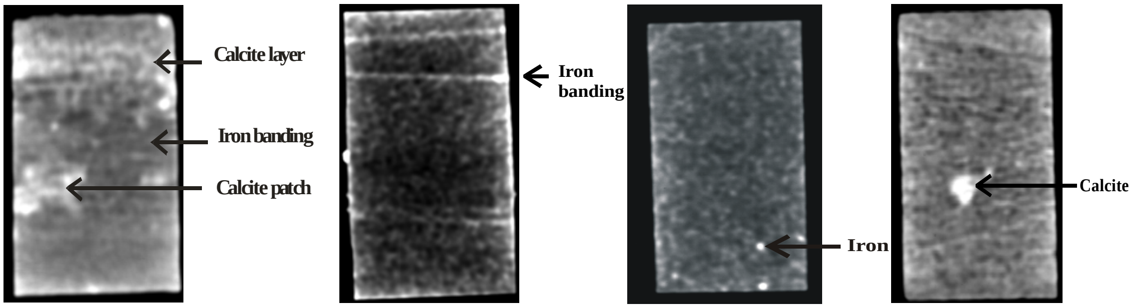
Figure 1: Development of the waterfront inside sample 8 of the Slick Rock Aeolian sandstone



(a) (b) (c) (d)

Figure 2: X-ray Computer Tomography (CT-Scanning) images of Slice 2 of Slick Rock Aeolian sandstone (a), Locharbriggs sandstone (b), Berea sandstone (c) and Fife sandstone (d)

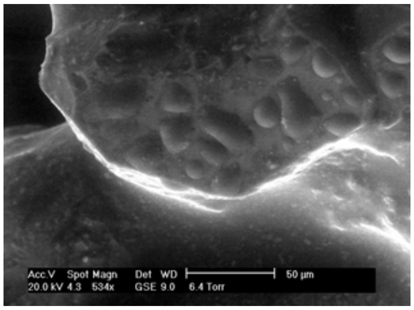


Figure 3: ESEM photo, showing water wet feldspar

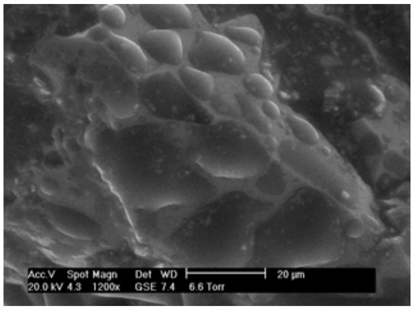


Figure 4: ESEM photo, showing water wet quartz

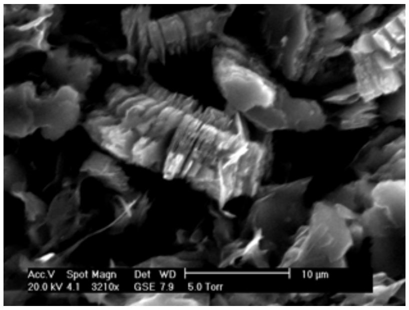


Figure 5: ESEM photo of a cement containing kaolinite, smectite and illite (Locharbriggs sandstone)

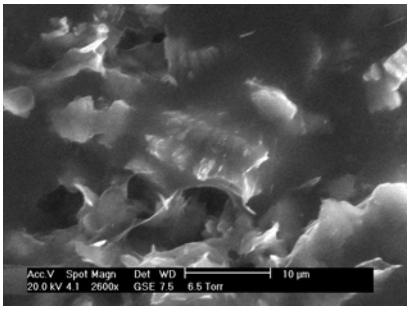


Figure 6: ESEM photo, showing the very water wet property of the clays (kaolinite, smectite and illite) (Locharbriggs sandstone)