MULTI-SCALE ROCK ANALYSIS FOR IMPROVED ROCK TYPING IN COMPLEX CARBONATES

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ABSTRACT

The evaluation of carbonate reservoirs is a complex task because of the inherent heterogeneities that occur at all length scales. Rock types may be defined differently at different scales and this introduces a challenge in capturing heterogeneity in a single rock volume. Heterogeneities at smaller length scales must be upscaled into larger scale volumes to better predict reservoir performance. The objective in this study is to define carbonate rock types at multiple scales and then upscale those rock types to the whole core level.

Representative core plugs were selected in a heterogeneous reservoir interval based on statistical distribution of litho-types in the core. The litho-types were described by porosity and mineralogy variations along the core length using advanced dual energy XCT imaging. Plug-scale rock types were defined on the basis of petrophysical data and geological facies. High-resolution micro to nano XCT images were integrated in the rock typing scheme. Those rock types were upscaled to the whole core level by linking the core litho-types to the plug data.

The core litho-types (porosity and mineralogy) gave good representation of the whole core heterogeneity and were reliable for selecting representative samples. This was qualified by X-ray diffraction mineralogy and plug porosity measurements. This allowed establishing the link between plugs and whole cores and hence upscaling rock type information to the whole core scale. The high-resolution digital images emphasized the different pore geometries in the samples and improved the definition of the rock types. Accurate porosity and permeability logs were derived along the core length and gave very good match with the plug data.

The paper presents an advanced and quick tool for representative sample selection and statistical core characterization in heterogeneous reservoirs. The identified rock types at multiple scales provided new insights into carbonate heterogeneity and gave upscaling options for rock types and petrophysical data. The upscaled rock types at the whole core level enhance the prediction of dynamic imbibition data along the reservoir column for improved reservoir performance.

INTRODUCTION

Proper core characterization is often overlooked in rock typing and sample selection studies. Random core sampling is usually performed and the selected plugs are not associated to the heterogeneity at the whole core level. This leads to unrepresentative selection of the core samples and their rock types, and hence raises questions about the effectiveness of the core data in reservoir models and their calibrations.

In this study, rock typing was first established at the whole core level by advanced dual energy CT scanning. Three main lithologies were identified that appeared to be the main control of the petrophysical variations along the core length. Representative plugs were selected from each lithology and analysed to confirm the rock types at the micro level. This was performed by Poro-Perm measurements, thin-section photomicrograph description, mercury injection analysis and high resolution XCT imaging.

DETAILED WHOLE CORE CHARACTERIZATION

X-ray CT imaging is a powerful non-destructive method used in the oil industry to evaluate the internal structures of reservoir cores. When the core is imaged by the Dual Energy technique it provides two distinct 3D images by using a high- and a low- energy setting. The high-energy images are more sensitive to bulk density (Compton Scattering effect) and the low-energy images are more sensitive to mineralogy (Photoelectric Absorption effect). The bulk density (RHOB) and effective atomic number (Zeff) values are computed independently for each CT slice along the core length [1].

Lithology Log and Statistical Analysis

In this study, 300 feet of reservoir core was imaged by the dual energy technique, and the bulk density (BD) and Zeff were calculated at 0.5 mm spacing. Figure 1(a) shows the bulk density and Zeff variations with three-color mineralogy log. The detected minerals were calcite (for Zeff larger than 14), dolomite (at Zeff around 13) and partially dolomitized core (at Zeff around 14) [2]. This mineralogical variation was also confirmed by XRD analysis performed on rock samples taken from each Zeff response along the core length. The identification of these minerals was obtained at very early stage of the study while the core was still in the barrel, hence providing a quick tool for detailed core characterization and representative sample selection. The volume percent of each mineralogy with respect to the total core volume was quantified from the whole core CT data and is presented in the pie chart in figure 2(a). The core is mainly composed of calcite with 66 vol%, 15 vol% dolomite and 19 vol% partially dolomitized core.

Core-Scale Porosity and Permeability

Representative samples were taken from each mineralogy along the core and were measured for helium porosity and gas permeability. The poro-perm data for the acquired plugs are plotted in figure 2(b), and shows two distinct correlations that are controlled by the different characteristics of the mineralogy in the reservoir. The dolomite and partially dolomitised plugs gave single trend with the dolomite samples at the higher poroperm range. Porosity ranges from 12 to 30 porosity unit and the permeability varies from 5 mD to 1000 mD. On the other hand, the calcite samples gave a lower permeability trend varying from 0.02 mD to 4 mD, while the porosity ranging from 8 to 25 porosity unit.

Figure 1(b) compares the plug porosity data with the core porosity log derived from the XCT bulk density data along the core length. The core porosity was calculated from the bulk density log and by using different grain density (GD) values for each mineralogy (GD: 2.71 g/cc for calcite, 2.85 g/cc for dolomite and 2.79 g/cc for partially dolomitized (dol/cal) intervals). There is an overall reasonable match between the plug helium porosity and the XCT-derived whole core porosity. Many plugs were taken in the core and gave different porosity values at almost the same depth intervals because of the core heterogeneity that cannot normally be characterized properly by plug-scale measurements. The comparison shows better matches for lower porosity range (i.e. <15%) at which the core shows less heterogeneity. In direct conventional comparison studies between whole core and plug helium porosity measurements, the whole core porosity data would normally be lower than the plug porosity [3,4], confirming our findings in this study.

Figure 1(c) compares the plug gas permeability with a permeability log derived along the core length from the porosity log and by using the plug poro-perm relations from figure 2(b). A very good comparison is observed between the core permeability log and the plug data. Very heterogeneous plugs overestimate core permeability by short-circuiting flow either because of fractures or vuggy porosity channels that do not represent the full diameter core [3,4]. Around two to three order of magnitude increase in permeability is seen in the dolomite intervals, which suggests large improvement in the rock transport properties with dolomitization for this reservoir under study.

ROCK TYPING

In order to understand the structure and porosity type of the rock types, thin-section and MICP wafers were cut from selected representative locations along the plug lengths. Figure 3 represents typical rock types identified from the different mineralogical variations at the whole core level. The figure presents (from left to right, in each RRT) 2D whole core XCT image, high-resolution micro CT image, mercury-derived pore-throat size distribution (PTSD) from mercury injection experiments and thin-section photomicrograph. The whole core image represents the location from which the plug was taken. The high-resolution micro images for the three rock types are taken at different resolutions to resolve the pore system. The dolomite rock type needed lower resolution at 4 micron/voxel where the corresponding mercury peak is at 10 micron pore throat radius and thin-section photomicrograph shows a complete dolomitised grainy system with inter-crystalline porosity. On the other hand, the pore system of the calcite rock type was only resolved by nano imaging at a voxel resolution of 0.064 micron. This muddy calcitic rock type is almost completely made of micrite with inter-particle porosity and a mercury peak at 0.7 micron. The partially dolomitized rock type gives the mercury peak at 3 micron pore throat radius and was imaged at 2 micron/voxel. Both the thin-section photomicrograph and the micro CT image show the dolomitized rock with precursor limestone as micritic particles. This integration of data confirms the rock types and enhances our understanding of these rock types at the micro level that can be upscaled to the whole core by the link of mineralogy.

The rock typing scheme presented in figure 3 can be populated in the whole core by the identified mineralogy as depicted in figure 1(a). In this perspective, the different minerals in this core are the main control of the petrophysical and fluid flow in the reservoir. The dolomitization that occurred has been a great improvement in the rock properties in the core, which is mainly composed of low permeability calcite. The dolomitization and partial dolomitization in the core have enhanced the permeability by 2 to 3 orders of magnitude and this was crucial for reservoir modeling and field development plan.

SUMMARY AND CONCLUSION

Dual Energy CT scanning was used to identify three different lithological variations along the core length by bulk density and effective atomic number. The core was mainly composed of low permeability calcite and higher permeability dolomitized intervals, which were crucial for enhanced petrophysical and fluid flow properties. Representative plugs were cut from the different lithologies and were grouped in three different rock types based on micro CT imaging, MICP analysis and thin-section description. The following can be concluded from this study:

1. Dual Energy CT scanning is a quick and powerful tool to accurately identify porosity and mineralogy variations along reservoir core lengths at early stages of the analysis.
2. The identified mineralogy in this core was found to be the main control of transport properties and fluid flow.
3. The CT-derived porosity and permeability logs at the core level showed good match with the plug data and gave averaged properties in more heterogeneous intervals.
4. Two distinct poro-perm correlations were established for the calcite and dolomitized rock types.
5. Rock typing was attempted at the following different scales, and was shown to give an excellent tool for improved understanding and upscaling:
    a. Whole core RRT by porosity and mineralogy logs
    b. Plug RRT by poro-perm
    c. Micro-level RRT by high-resolution CT, MICP and thin-section

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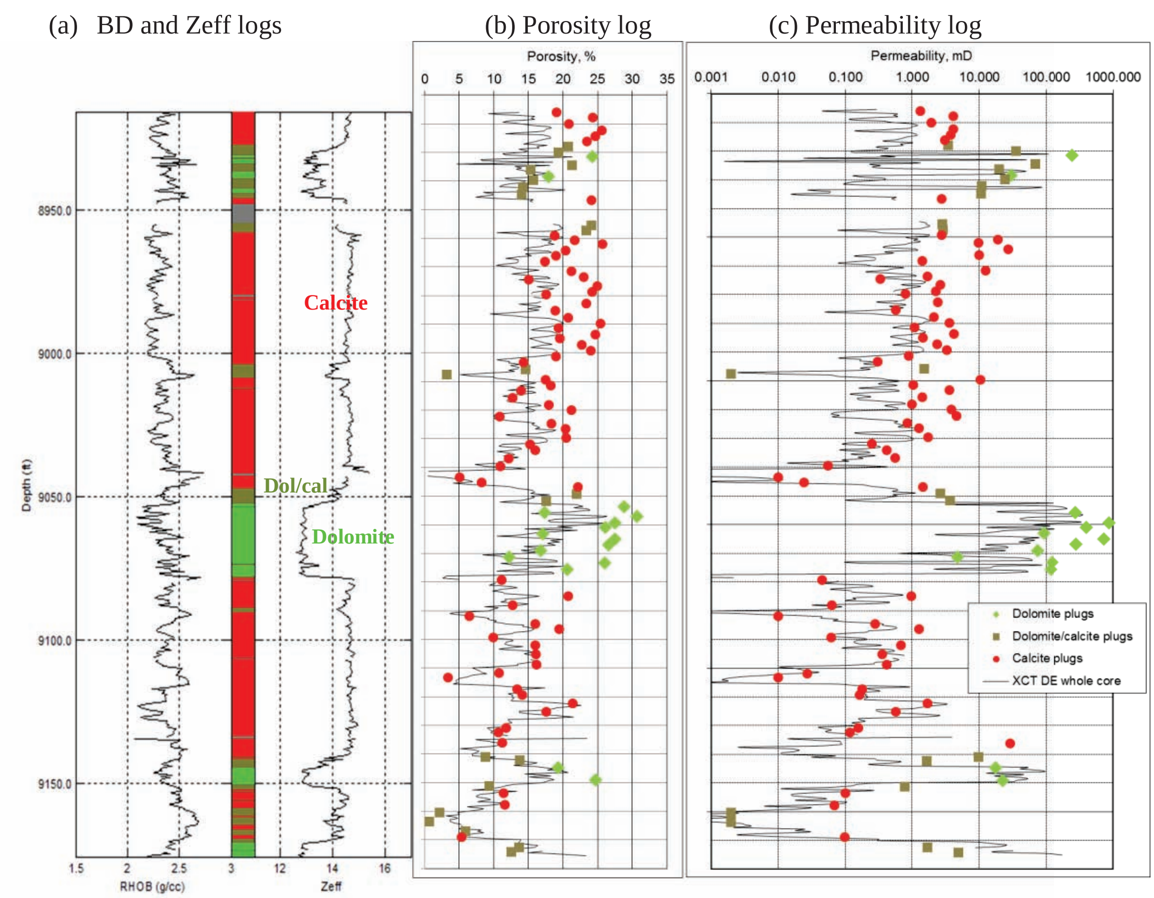

Figure 1 (a) XCT Dual Energy-derived bulk density and Zeff logs along the core length with colored mineralogy log based on Zeff variation. (b) Comparison of DE-derived porosity with plug porosity. (c) Comparison of DE-derived permeability with plug permeability.

(a) (b)

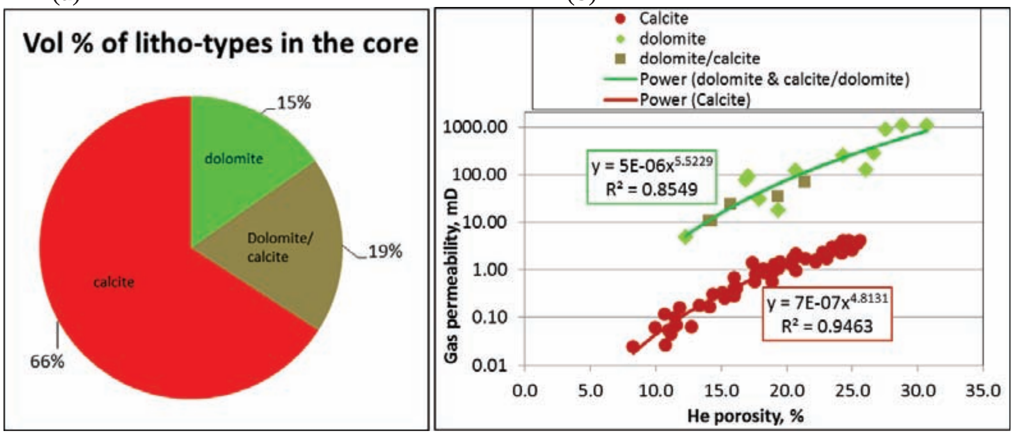

Figure 2 (a) Dual Energy-derived statistical analysis of the litho-types in the core (data from figure 1a). (b) Poro-perm relations for the calcite and the dolomitized plugs.

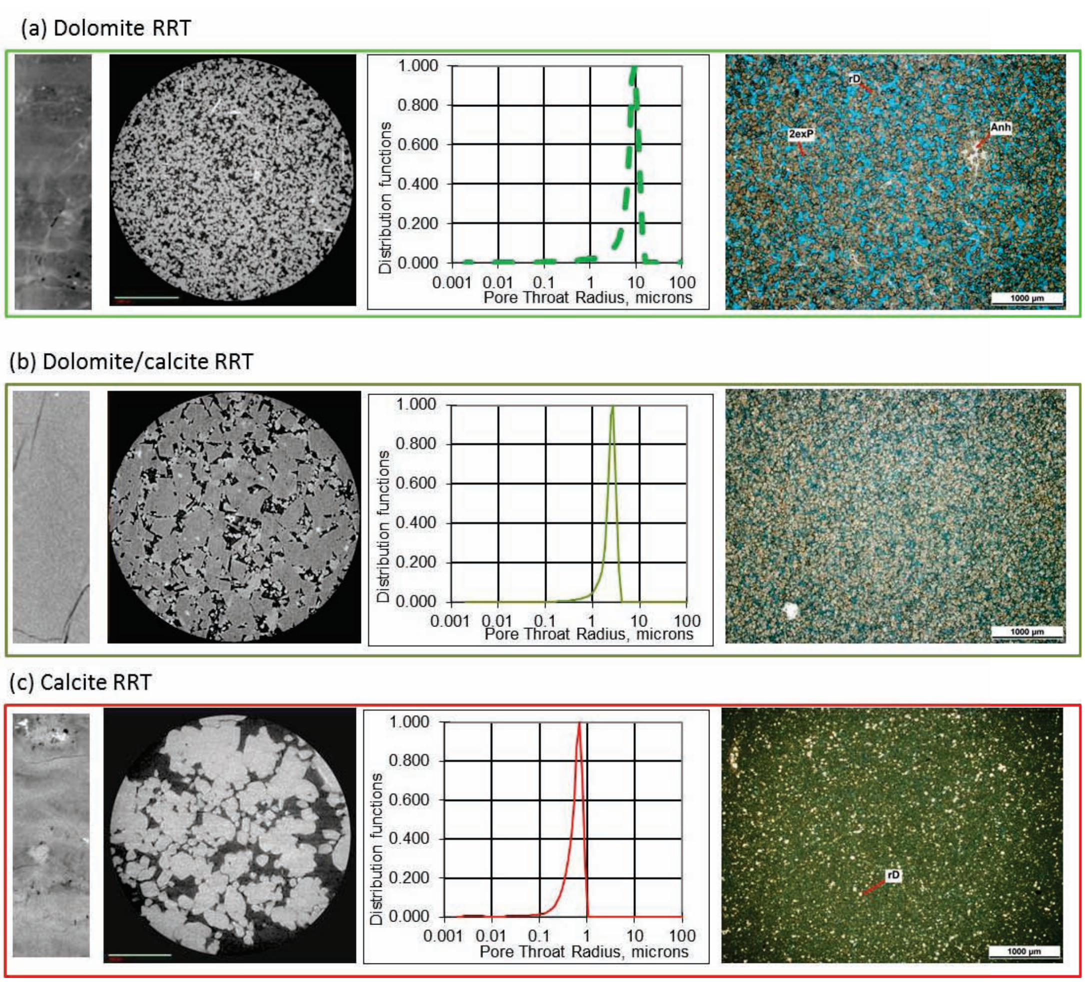

Figure 3 From left to right (in each RRT): 2D whole core XCT image, high resolution micro CT image, mercury-derived pore-throat size distribution (MICP) and thin-section photomicrograph.