Pore System Structure Assessment Using BSE-SEM Data

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Summary

This work investigates the potential of BSE-SEM analyses in assessing the pore system structure. Twenty-three carbonate and clastic samples were analysed using a QEMSCAN system, which enables a good assessment of the macropore system (pore larger than 10µm). It defines the macropore system volume and also delivers pore length distribution. The pore length distributions are integrated with plug-NMR results; a good match is observed between the two type of results, which enables a calibration of the T2 relaxation time againts pore sizes. Compared to NMR data, BSE-SEM data provide real pore measurements, which could be more accurate to use in permeability calculations.

Introduction

The characterisation of the pore system in carbonate rocks is key for permeability predictions. For equal porosity values, permeability varies significantly depending on whether the pore system is micropore-dominated, mixed micro/macropore or macropore-dominated. Variations can reach 2-3 orders of magnitude. For this reason, the characterisation of a carbonate pore system structure is crucial for permeability prediction. Pore system characterisation is most accurate when thin-sections are analysed and percentages of macropores and micropores are determined. Most of these data are semi-quantitative and thus, biased on manual, human assessment. Where rock samples are not available, NMR (Nuclear Magnetic Resonance) results provide indirect information on pore system structure. NMR data are used together with porosity values to calculate permeability using either the SDR (Schlumberger-Doll Research) or the Coates models. However, NMR pore structure assessment can sometimes be limited due to the coupling effect through the aggregation of two pore size families that are very close in size. Some errors in pore size evaluation are therefore possible. Moreover, data derived from NMR are typically not realistic since pore sizes are assessed through the measurement of the relaxation time (T2) of free fluid molecules present within pores. Some calibrations between petrographic observations or MICP with NMR have been published (Han et al. 2018; Vincent et al. 2011), however, calibration of T2 relaxation time on pore size is impaired by the qualitative nature of petrographic data.

This work investigates the use of automated BSE-SEM (Backscattered electron - Scanning electron microscopy) in providing quantitative information on pore system structure from thin sections. In this paper, porosity evaluation from automated BSE-SEM is compared against semi-quantitative or image analysis methods performed on carbonate thin sections. This comparison highlights the benefits and limitations of each of the approaches. In addition, pore structure assessed by automated BSE-SEM on both carbonate and clastic samples is integrated with petrophysical data (e.g. NMR) to assist in the calibration of T2 relaxation time and measured pore sizes. Outcomes of this calibration is likely to help in the refinement of permeability prediction based on log porosity, MICP and/or NMR-derived pore structure data.

Approach and automated BSE-SEM analysis methodology

Ten carbonate and thirteen clastic samples were selected for automated BSE-SEM analysis. These samples represented a wide range of reservoir properties and pore systems. While clastic samples were represented by sandstones within which macropores are well developed and relatively connected, the carbonate samples illustrated different pore system structures (Figure 1).

After thin section preparation, porosity assessment was carried out using three methods, detailed as follows:

- Automated mineralogical analysis was carried out using a Quanta 650F Scanning Electron Microscope, which comprised a scanning electron microscope (SEM) with two energy dispersive X-Ray detectors (EDX), a backscattered electron detector (BSE), a microanalyser and an electronic processing unit. This automated acquisition was initially designed for sample mineralogy analysis, which is achieved through the QEMSCAN® mode of operation. EDX measurements are generally used to determine the sample mineralogy of clastic samples in the Oil & Gas industry, but these data were not used for the purpose of this work. BSE brightness measurements enabled the identification of pore spaces within the samples. Resulting data were processed using the iDiscover software suite, which provided a total pore volume, pore distribution maps and pore length quantification. Automated BSE-SEM analyses were performed at 10µm on a 1cm^2 area of the clastic and carbonate sample slides. At this resolution, only minerals or pores greater than 10µm could be measured and quantified in the image analysis. In this work, we considered the micropore/macropore cutoff to be 10µm (e.g. Cantrell and Hagerty 1999).

- A semi-quantitative analysis on carbonate samples visually estimated the relative abundances of elements, cements and pores across the entire thin section areas, supported by comparison charts.

- Image analysis was carried out using the software J-MicroVision (Roduit 2019), which enabled the quantification of porosity (blue areas) on the slides. Three images at x2.5 magnification per sample were taken in order to generate an average sample heterogeneity. The analyses were processed using the 'Background Extraction' module and IHS channel.

Comparison of different porosity evaluation approaches

The results of semi-quantitative, image and automated BSE-SEM analysis conducted on the 10 carbonate samples were compared. This comparison aimed to assess the difference in terms of total pore volume and value of data provided by each method. Overall, the three approaches underestimated pore volume by 5 to 10% compared to porosity measured by Conventional Core Analyses (CCA; Figure 1A). The underestimation is likely to be caused by: 1) the occurrence of micropores not visible in thin section and thus, not captured by any of the three methods, 2) the fact that porosity data was captured from a 2D section.

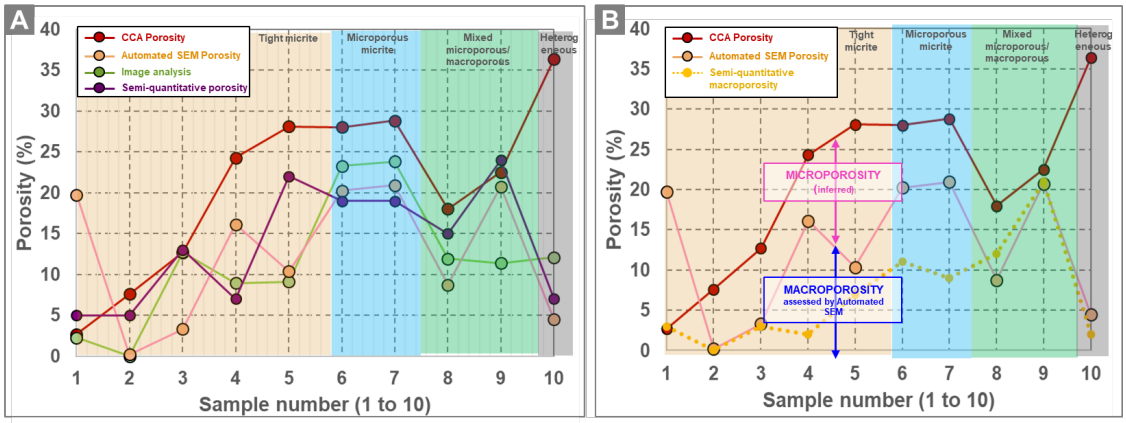


Figure 1: *A) Porosity evaluation of 10 carbonate thin section samples using semi-quantitative, image analysis and automated BSE-SEM analyses compared to CCA porosity measurements. B) Semi-quantitative macroporosity evaluation compared to BSE-SEM and CCA porosity evaluation. Automated BSE-SEM analysis has been carried out at 10µm resolution on whole thin section. As such, macroporosity (>10µm in this study) is considered to have been captured by the analysis.*

In summary, comparison between the three methods showed automated BSE-SEM porosity analysis is the preferred approach for the following reasons:

- Porosity evaluation was carried out consistently across different samples and was not biased by manual, human interpretation, as per the semi-quantitative approach. It has been noted that macropore abundance was underestimated by the semi-quantitative approach, as compared to automated BSE-SEM (Figure 1B).
- Image analysis using JMicroVision is applicable for samples that did not contain ferroan dolomite. This mineral is blue stained and is thus taken into account in the analysis.
- Automated BSE-SEM characterises pore sizes and provides abundances for specific pore size families. The analysis was run at 10µm measurement spacing and thus captures macroporosity (considering a macropore/micropore cutoff of 10µm in this case). As such, microporosity is calculated from the difference between CCA porosity measurement and automated BSE-SEM porosity.

Pore length distribution

The maximum length of each pore was measured by automated BSE-SEM and abundances (percentage or count) of each pore size family (e.g. 100-200µm) were captured for each sample. Pore size data for the carbonate samples, along with macropore and micropore abundances, were used in

reservoir quality assessment in order to provide additional information on reservoir quality controls (Figure 2). Average macropore size was calculated from the weighted average abundance for pores larger than 10µm. In this example reservoir quality distribution is controlled by the development of both macropores and micropores as well as macropores size.

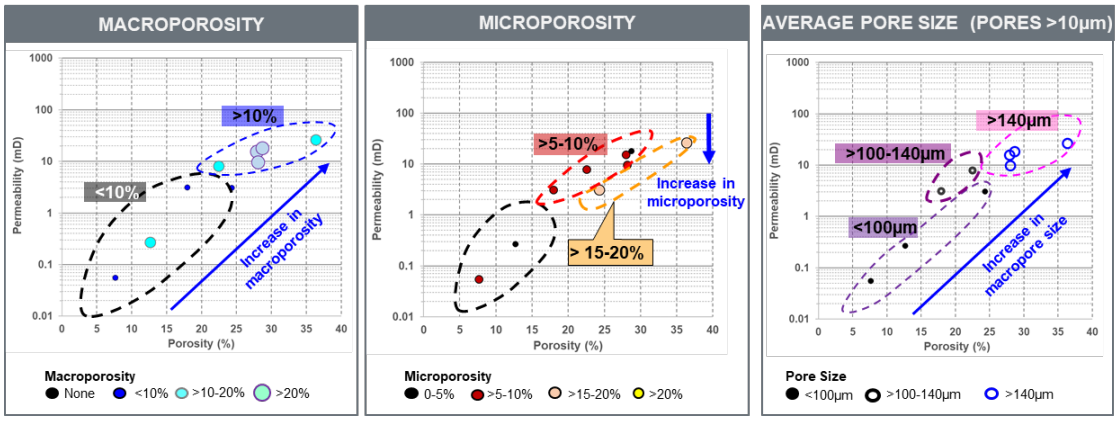


***Figure 2**: Reservoir quality assessment using automated BSE-SEM data. Data coded by A) macropore abundance, B) calculated microporosity abundance (CCA – automated BSE-SEM macroporosity; refer to the previous section for more details), C) average pore size (of pores larger than 10µm).*

Calibration of NMR with pore length distribution

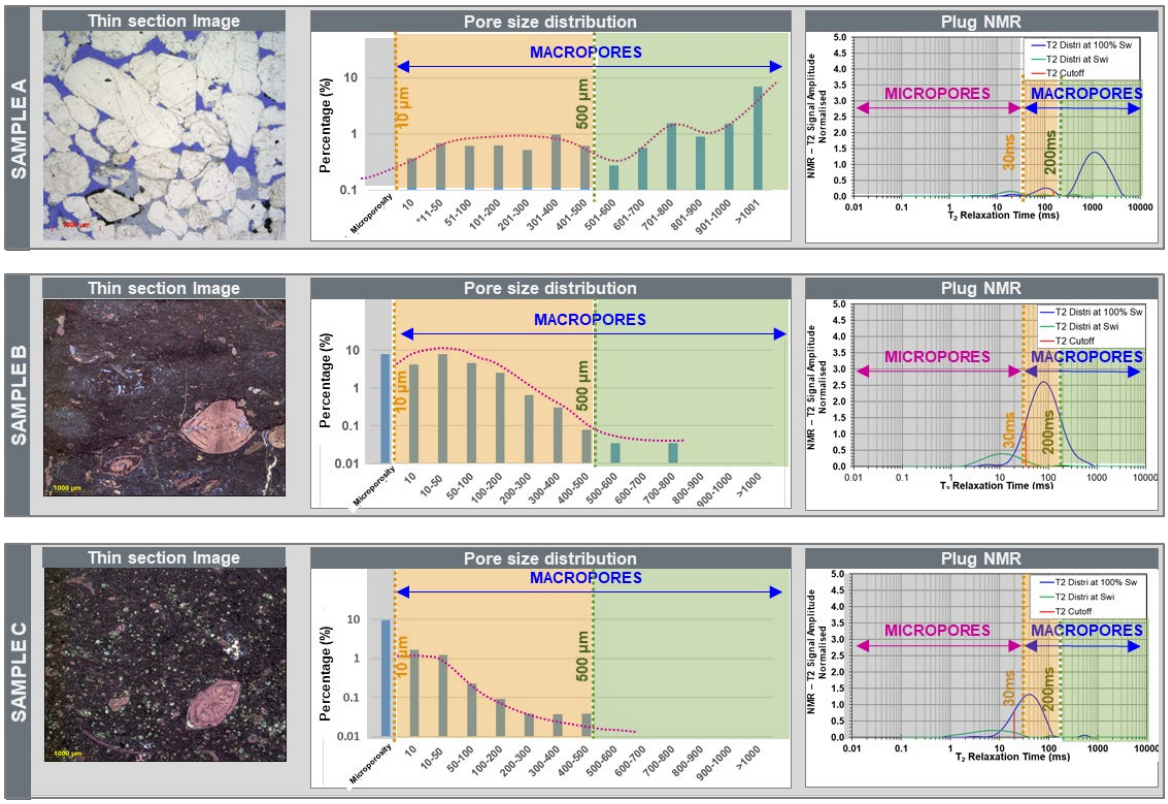
The pore length distribution of 10 carbonate and 13 clastic samples were measured by automated BSE-SEM and were integrated with NMR results to help in the calibration of T2 relaxation times and the determination of pore size. Three key samples are displayed on Figure 3 to illustrate this calibration.

The pore length distribution graphs display the percentage of macropores over 10µm. Micropores are considered to be smaller than 10µm and their abundance is calculated from CCA porosity and abundance of pores larger than 10µm.

Based on a comparison of pore length distribution graphs of 23 clastic and carbonate samples and their respective T2 relaxation curves, the micropore/macropore cutoff of 10µm is interpreted to have been set at a T2 of 30ms. Moreover, the trough recorded at 200ms in T2 curve in Sample A is likely to correspond to the reduction in pore size recorded between 500-600µm. Micropore/macropore cutoff at a T2 relaxation time of 30ms is consistent with Han et al. (2018) but is different to the value of 200ms interpreted by Vincent et al. (2011). This discrepancy might indicate that a calibration is likely to be required for each NMR analytic system before pore sizes are extrapolated to T2 relaxation curves

While NMR results capture the full pore system, T2 relaxation curves can aggregate different pore families that are closest in size. This would result in subtle errors in the estimation of the pore size average through the T2 geomean. For instance, subtle variations in pore size abundance between 500 and 1000µm are not captured by the T2 relaxation curve of Sample A (Figure 3). Using automated BSE-SEM data together with NMR results could improve the equations to calculate permeability, as the macropore system structure would be better assessed.

***Figure 3 (next page):** Petrographic and petrophysical characteristics of three key samples. Sample A is a sandstone while samples B and C are limestones. Microporosity is calculated from the difference between CCA porosity and measured automated BSE-SEM porosity, the latter is considered to represent macroporosity.*



Conclusions

This work shows that automated BSE-SEM analysis is more reliable and consistent in porosity assessment than semi-quantitative methods, a process which is typically biased by manual, human description and underestimates macropore abundance. However, petrographic description is still required to capture pore type information. Furthermore, compared to image analysis, which provides with also percentage of visible porosity, automated BSE-SEM enables the determination of pore size in addition to pore volume. Pore length distribution is an additional dataset that can be implemented into reservoir quality assessment and this enables calibration of NMR T2 relaxation time with pore size. A proposed way forward is the integration of pore length distribution measurements into equations for permeability calculation followed by comparison of the automated BSE-SEM calculated permeability with log or NMR-derived calculated permeability.

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