Mineralogical controls on organic-hosted pore volume and pore size – Duvernay Formation, Alberta, Canada

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Summary

Organic matter contributes significantly to total porosity in self-sourced hydrocarbon reservoirs. However, the main controlling factor(s) for development and preservation of organic-hosted porosity are not well understood. By examining the Duvernay Formation of western Canada this study demonstrates an association between matrix composition and organic-hosted porosity. In this study, the contribution of organic- and inorganic-hosted pores in total porosity were quantified by deconvolution of laboratory-based nuclear magnetic resonance (NMR) curves. Significant secondary feldspar dissolution porosity in the T2 range of clay-bound water is observed in the wet gas window near Fox Creek.

Methods

Core samples were analyzed from three wells (Chevron Fox Creek 08-15, Chevron KaybobS 14-20, ECA Saxon 11-08) in the late oil to dry gas window. Mineral composition was obtained from a combination of inductively coupled plasma – mass spectrometry (ICP-MS), X-ray diffraction (XRD), and scanning electron microscopy – energy dispersive x-ray spectroscopy (SEM-EDS). In order to obtain total organic carbon (TOC), thermal maturity, and organic matter composition programmed pyrolysis was performed. A subset of samples underwent programmed pyrolysis with the extended slow heating cycle (ESH; Sanei et al., 2015) in order to quantify light hydrocarbons, medium to heavy weight hydrocarbon residue, and solid bitumen/kerogen fractions. Maceral characterization and bitumen reflectance was derived from petrographic analysis. Porosity measurements were obtained using nuclear magnetic resonance (NMR) on dried and brine-saturated samples, helium porosimetry, mercury injection capillary pressure (MICP), and focused ion beam – scanning electron microscopy (FIB-SEM) with image analysis.

Results

Despite significant variation in porosity values from method to method, measured porosity typically correlated positively to TOC. This correlation was notably weak in the KaybobS well, in NMR-derived porosity, and for high-TOC samples. Scatter in the TOC vs porosity relationship was resolved by using threshold values in the SiO_{2_bio}/TOC (Fig. 1; SiO_{2_bio} is biogenic silica) and Muscovite/TOC ratios.

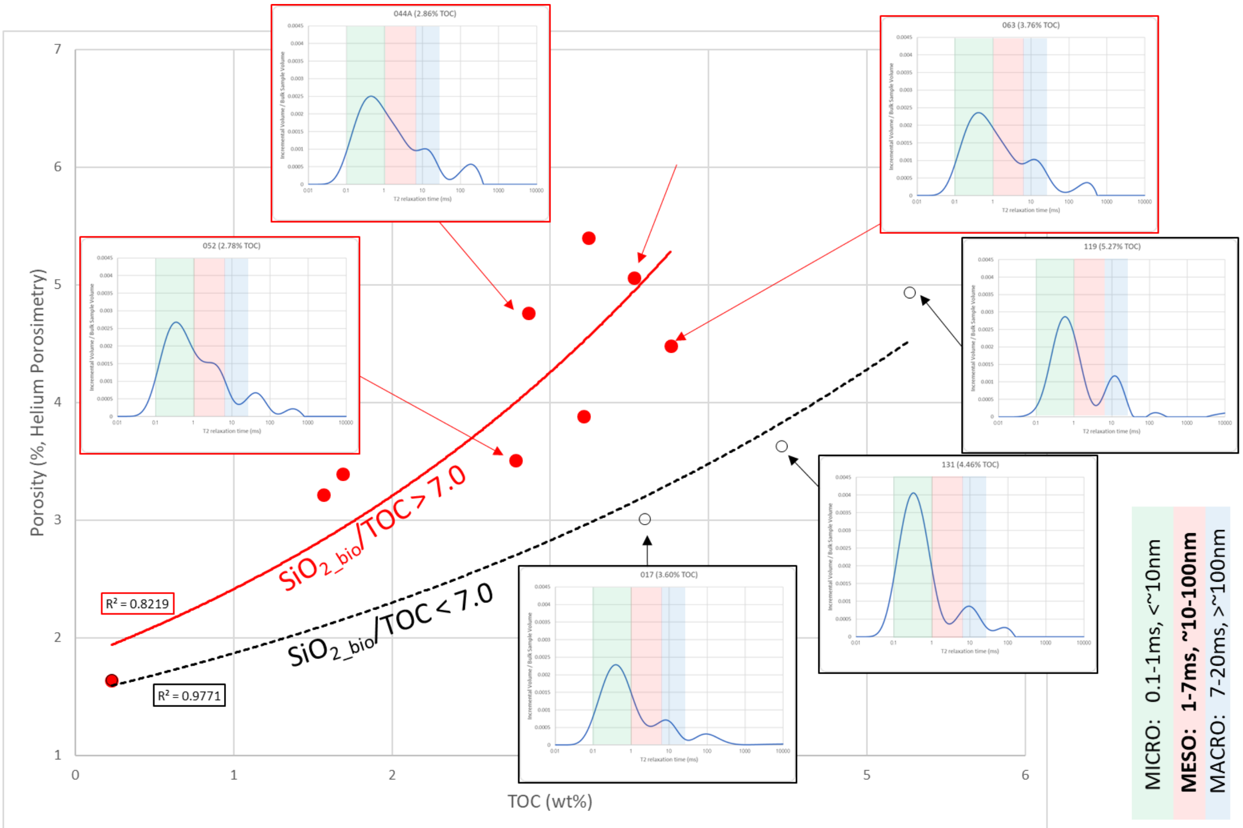

Figure 1. Total organic carbon vs porosity from helium porosimetry in 12 Fox Creek samples. Samples with high SiO_{2_bio}/TOC have enhanced porosity. Porosity enhancement occurs in the mesoporosity range as shown by the NMR T2 distributions for brine-saturated samples.

Deconvolution of NMR T2 distributions allowed for the correlation of T2 peak volumes to mineralogy and organic geochemistry data. By measuring T2 relaxation time on samples in both dried and brine-saturated conditions, bound fluid volume was differentiated from mobile fluid volume (Fig. 2).

In the Fox Creek well, high SiO_{2_bio}/TOC was found to significantly enhance organic-hosted porosity and mobile fluid volume. Samples with low SiO_{2_bio}/TOC had reduced mobile fluid volume and organic matter was typically microporous. In the Fox Creek well, which has 10 wt% average clay (XRD muscovite + illite), NMR dry peak 1 (low T2; immobile fluid) was strongly correlated to potassium feldspar, and not clays. This result was unexpected since this is the typical range of clay-bound water. Potassium feldspar dissolution was confirmed using SEM-EDS, and is consistent with the suggestion that K-feldspar dissolution is common in the wet gas window of the Duvernay Formation (Dong et al., in press), potentially due to the presence of organic acids (Baruch et al., 2015).

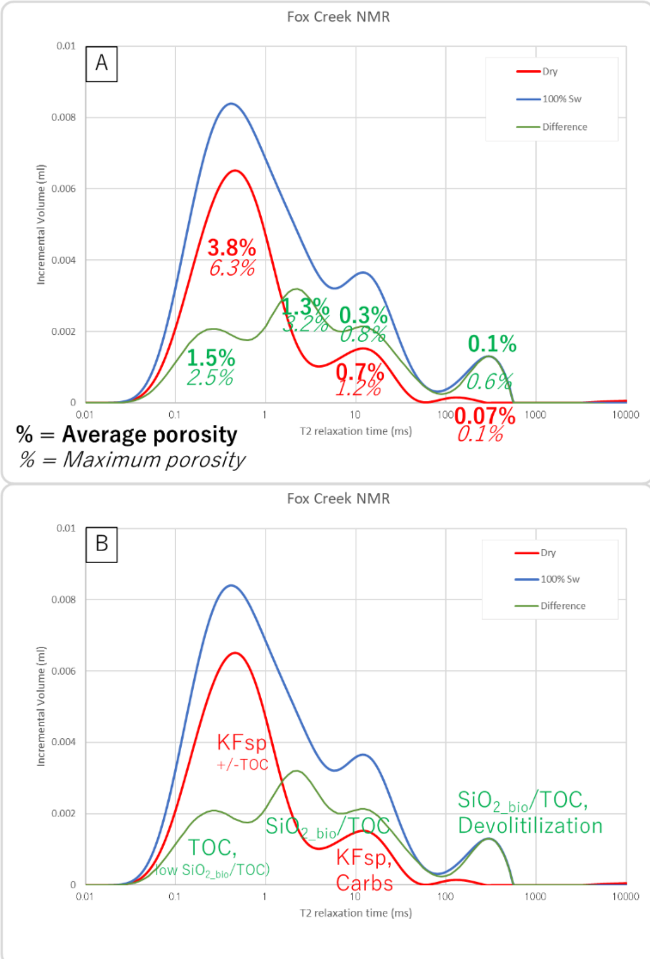

Figure 2. A) Average and maximum volumes of NMR T2 peaks from 10 Fox Creek samples. B) Summary of parameters that control the volume of each NMR peak.

In the KaybobS well, with less SiO_{2_bio} and more clays, muscovite exerted a dominant control on both organic- and inorganic-hosted porosity. Samples with high Muscovite/TOC had enhanced organic-hosted porosity. Solid bitumen macerals isolated in the clay-rich matrix had larger pores than well-connected macerals. NMR dry peak 1 volume was dominated by clay-bound water.

Although interpretation of these results is ongoing, it appears as though organic porosity development and/or preservation may be influenced by matrix composition or fabric. High SiO_{2_bio}/TOC has been shown to enhance organic-hosted porosity volume and pore size relative to low SiO_{2_bio}/TOC samples. This relationship is likely associated with the role that SiO_{2_bio} plays on sediment compaction. Dissolution, recrystallization, and replacement of the siliceous skeletons of radiolaria and sponge spicules has been interpreted to occur early after burial (Knapp et al., 2017). Silica re-precipitates as microcrystalline quartz throughout the matrix, enhancing hardness and brittleness (Dong et al., 2018). Early emplacement of microcrystalline quartz cement may have acted to limit compaction and preserve primary porosity. Biogenic silica could enhance organic-hosted porosity in two ways:

1) *Limiting occlusion of organic-hosted pores.* Pore-filling solid bitumen (migrated oil which has thermally cracked to solid bitumen) is readily identifiable in SEM and can be seen mixed with separate phases of solid bitumen or kerogen that have different porosity characteristics (Fig. 3). Compaction-limiting SiO_{2_bio} preserves primary porosity, which can then be filled with oil. The availability of open pore space may mean less oil is forced into or trapped within organic-hosted pores.
2) *Limiting compaction of organic-hosted pores.* Pore-filling solid bitumen is not load-bearing due to a rigid siliceous matrix.

The Muscovite/TOC ratio is interpreted to be a proxy for maceral isolation. Isolated bitumen macerals (high Muscovite/TOC) are typically macroporous, potentially because they are surrounded by low-permeability matrix that inhibits migration of bitumen and limits occlusion of organic-hosted pores. An alternative interpretation is that clay catalysis locally enhances thermal maturity and influences porosity generation.

Other processes that may act in concert with occlusion and compaction are phase separation/coalescence and oil/bitumen fractionation as a function of matrix permeability or bitumen network connectivity. Ongoing analysis will examine in more detail the organic geochemical properties and molecular structure of porous and non-porous macerals to shed light on these processes.

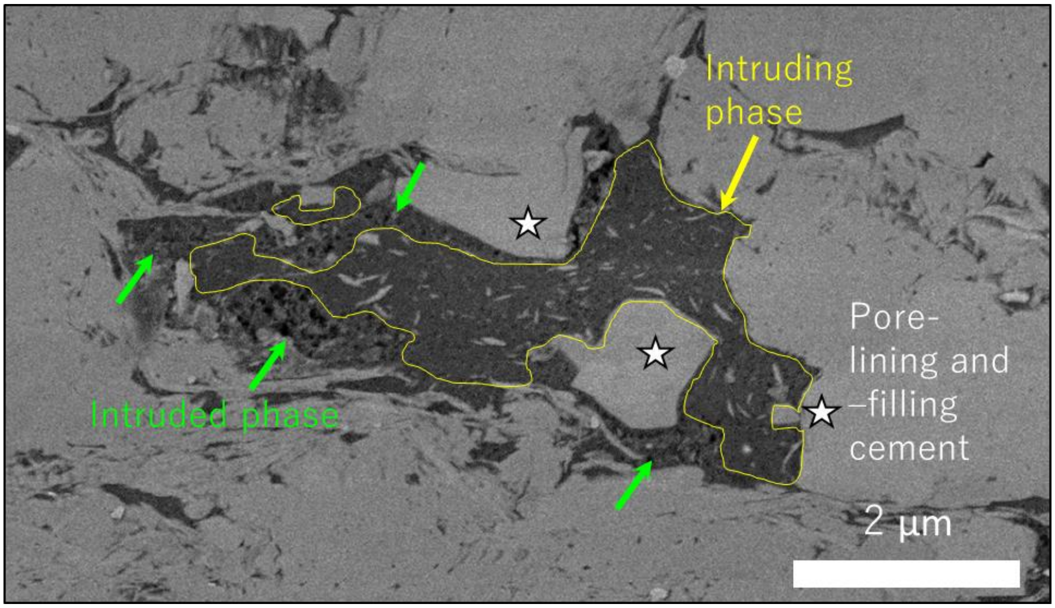

Figure 3. Pore-filling solid bitumen (thermal product of migrated oil; yellow polygon) is seen penetrating into a separate bitumen or kerogen phase (green arrows) that has larger pores. Pore-filling solid bitumen occurs in cement-lined pores, suggesting emplacement after mineral growth (Loucks et al., 2014). Floating clay platelets have likely been entrained in a viscous flow.

Novel Information

This study presents an interesting examination on the factors influencing organic-hosted porosity. Ratios of biogenic silica and muscovite to TOC act as proxies for subsurface processes, and offer an explanation for local variability in organic-hosted porosity. Another important result of this study is the identification and quantification of major contributors to total porosity in the studied samples. In particular, the demonstration of significant K-feldspar dissolution porosity in the NMR T2 range of clay-bound water has implications for the interpretation of reservoir properties using downhole NMR logs.

By presenting a more robust explanation of organic and inorganic-hosted porosity in mudstone reservoirs, we open the door to more accurate models of hydrocarbon storage and fluid flow.

Acknowledgements

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