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Porosity evolution in oil-prone source rocks

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HIGHLIGHTS

- Organic rich shales contain considerable amount of porosity in the oil window.
- Extracting the entrapped bitumen allows us to effectively access and measure porosity.
- Kerogen porosity is the dominant pore morphology in organic rich shales (ORS).
- Specific surface area and porosity are directly related to TOC in ORSs.

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ABSTRACT

The origin of porosity and mechanisms of fluid flow in the presence of organic matter and clay minerals in source rocks are poorly understood. Burial and maturation of the source rock modify or create the pore systems in these rocks. Kerogen decomposition and consequent shrinkage may change the load bearing state of the minerals and organic matter and affect pore system since early stages of maturation. Geochemical evidence confirms that the hydrocarbon expulsion process (i.e. primary migration) is not 100% efficient. Expulsion of hydrocarbon is mainly driven by (1) pressure increase in the source rock due to solid kerogen conversion and volume increase and (2) continued compaction of the sediment. Converted organic matter is partly retained in the source rock diverse framework constituents. Quantitative measurement of and determining producibility of the retained hydrocarbon in the source rock is to date highly debated. The source rock hydrocarbon storage capacity is controlled by pore-hosting particles, pore system topology and rock–fluid interactions.

The presence of organic matter and clay minerals affect log responses by generally overestimating porosity, because the low density kerogen is not accounted for, and together with low resistivity caused by presence of clay minerals can result in erroneous saturation calculations; thus, accurate reserve estimation often is challenged if the impact of low organic matter density is not explicitly addressed.

In order to understand porosity evolution and the interaction of organic byproducts (i.e. bitumen and pyrobitumen) with rock minerals during thermal maturation, one must study source rock samples with different maturities. For this reason, ten Bakken Shale samples with varying maturity and mineralogy were selected in this study. Pore size distributions (PSD), specific surface areas (SSA) and geochemical characteristics of the samples were measured in native state and after successive solvent extraction.

The PSD and SSA measured after each extraction shows recovery of the pore system with successive cleaning. Most significant was the recovery of kerogen-hosted pores with removal of soluble, oil-like organic material. Using successive extractions we are able to determine the evolution of organic matter porosity through maturation which is otherwise not feasible using visual techniques or other conventional laboratory procedures.

1. Introduction

Pore size distribution (PSD), tortuosity, pore aspect ratio, and surface properties are the main pore characteristics which are defined by rock composition, fabric and its burial and diagenetic history. These aspects influence the petrophysical characteristics

Abbreviations: TOC, total organic carbon; SEM, scanning electron microscopy; HI, hydrogen index; SSA, specific surface area; PSD, pore-size distribution; BET, Brunauer–Emmett–Teller (BET) theory.

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of the rock as well as our measurement of these properties. Accessibility of the pore system by the displacement fluid, wettability and surface properties of the grains are the main controls on acquiring reliable and consistent laboratory measurements.

In low porosity rocks with permeability in the nanoDarcy range, porosity measurement comes with unique challenges, e.g., due to, but not limited to, nanometer-sized pores and reactive clay minerals. Conventional methods to measuring porosity and PSD in fine grained, ultra-tight rocks usually yield inconsistent values [1–3]. Defining effective porosity in ultra-tight self-sourcing reservoirs with clay minerals and/or organic matter presents yet another challenge. Clay porosity in conventional reservoirs is considered as an ineffective pore system in storage and flow. Recent studies have questioned this assumption and shown that at certain circumstances, the clay minerals could improve storage and/or flow of hydrocarbons in ultra-tight rocks [4].

Log-derived porosity is calculated from density, neutron and/or sonic logs. These calculations require knowledge of density, hydrogen index and mechanical properties of rock fragments. Kerogen has lower density, lower elastic modulus, higher Poisson's ratio and higher hydrogen content than inorganic minerals [5–8]. Scarcity of accurate measurements of kerogen properties and high contrast between physical properties of kerogen and inorganic minerals makes conventional log interpretation techniques difficult to apply to organic rich rocks.

Pore systems in organic rich rocks matrix can be divided into three pore types as defined by Loucks et al. [9]. Two types of pores are associated with the inorganic minerals (as interparticle and intraparticle mineral porosity) and the third type is associated with the organic matter (intraparticle organic porosity). All types of pores evolve since the time of deposition due to burial, diagenesis and maturation. Clay minerals also undergo significant porosity reduction due to compaction [10].

Porosity in kerogen may exist in the original particle at the time of deposition (e.g., original cellular microstructure in plant material or recycled thermally mature vitrinite), but more commonly, in Type II organic matter it is generated during burial, with early stages of porosity development due to decomposition and catagenesis. Kerogen porosity (if preserved) is often filled with bitumen at early stages of maturation [11,7]. Confirming existence of intraparticle kerogen porosity using SEM image analysis techniques, based on material density contrast, is very challenging since the density of kerogen and bitumen are close. Kuila et al. [12] studied nano-scale pore structure of source rocks by comparing the PSD before and after removal of organic matter by NaOCl treatment. They found significant reduction in abundance of nanometer-size pores after removal of organic matter in mature source rocks indicating storage space within the kerogen. Prasad et al. [6] have shown that with increasing maturity, kerogen particles are sheltered in a supporting frame of stiffer minerals. It is speculated that intraparticle organic porosity in kerogen is well preserved if the kerogen particles are sheltered by load bearing stiff minerals [13]. Determining the fraction of organic matter that is sheltered by such framework of stiff detrital or diagenetic minerals is therefore essential.

The interaction between organic matter maturity and minerals changes effective porosity and other geophysical properties of the mudrocks [14]. Sorption and absorption of hydrocarbon in the organic matter and on the surface of clay minerals also affect the hydrocarbon storage capacity and fluid flow [15–18]. Bitumen and other byproducts of kerogen maturation occupy clay and kerogen porosity in the early stages of oil generation [7,12]. Different mechanisms through which clay minerals and organic matter may interact are widely studied [19–23]. The interaction of clay minerals and organic compounds is mainly governed by the electrically charged surface of the clay minerals and the polar nature of some functional groups present in the bitumen [20]. Based on tendency of some organic functional groups to be adsorbed at clay exchange sites [19–23], it is possible that some organic compounds form stronger bonds with external clay surfaces, replacing clay bound water and consequently dehydrating the source rock. This phenomenon may cause a dramatic increase in resistivity by eliminating the water from interparticle clay porosity and occupying cation exchange cites of the clays.

Previous studies on characteristics of the pore system in source rocks provide limited information about how their pore systems evolve. These studies are mostly focused on investigating the pore system in samples as received with limited pre-treatments or with limited discussion on how pretreatments affect measurements of porosity and PSD [9,12,13,24–26]. We previously observed that considerable amount of bitumen is generated and stored in the source rocks in the oil window [7].

Lack or presence of bitumen in the pore system may introduce significant discrepancy in our evaluation of porosity and pore characteristics [27–30]. However, there are no sharp boundaries between bitumen and hydrocarbons; converted kerogen (hydrocarbons or bitumen) are by definition soluble in organic solvents. If anything, it is the converted organic matter that can contribute to production from source rocks. Therefore, determining the amount of storage specified to the soluble hydrocarbons provides an estimate of effective porosity in organic rich shales. In this study, solvent extraction was performed to determine what portion of the total pore space is excluded from quantification due to oil trapped in pores and to understand the storage and flow capacity of source rocks in the oil window.

2. Material and methods

2.1. Visual techniques

One of the most debated topics related to pore systems in organic rich shales at the oil window is the contribution of each pore hosting grain in total voidage and accessibility and contribution of different pore types in hydrocarbon storage and ultimately, production. Mineralogy, organic richness and thermal maturity determine the types of pores, interaction between generated hydrocarbons and minerals, and control changes in pore-hosting particles.

Visualization techniques have been widely used for petrographical analysis. SEM imaging and thin section analyses are used to understand pore structure, pore morphology and effect of compaction and diagenesis on pore systems. Due to fine-grained nature of mudrocks and complex sub-micron sized pores, 2-D and 3-D SEM imaging techniques have received broad attention for studying porosity and pore structure of mudrocks [9,31–35]. High resolution imaging and image processing techniques have led to development of a new branch of rock physics, the so-called "Digital Rock Physics". However, since digital rock physics is dependent on high resolution images, it is biased toward visible porosity. A considerable portion of the pore system may remain saturated with bitumen and will be counted as a part of solid organic matter due to low optical and density contrast with the kerogen.

This study is focused on quantifying porosity in organic rich rocks at different maturities with emphasis on bitumen-filled porosity in the oil window. This porosity quantification can help understand evolution of porosity and porosity topology in organic rich shales as well as improve digital rock models.

In the following section, we discuss petrographic results of three Bakken Shale samples at immature, mature (oil window) and overmature (gas window) states to visually and quantitatively examine porosity evolution with increasing thermal maturity.