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Permeability evaluation based on Nuclear Magnetic Resonance analysis for gas hydrate reservoir

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Permeability (or hydraulic conductivity) is one of the most important parameters for analyzing hydraulic behavior of underground. For example, in the geotechnical engineering, permeability is necessary to calculate water inflow and draw down of water level during excavation, to predict the deformation time due to the consolidation, and to evaluate the barrier of the ground for radioactive waste disposal. In the petroleum industry, permeability is considered an essential parameter which is directly linked to the productivity of oil and natural gas. Therefore, predicting permeability using wireline logging or logging while drilling (LWD) is required during the assessment of the reservoir. Nuclear Magnetic Resonance (NMR) logging is performed at this point. Low-field NMR measurements are sensitive to the hydrogen proton, 1H, in liquid water but not to the 1 H bond in solid form, making it possible to obtain the bulk water volume. In addition, the hydrogen proton NMR- T_2 (transverse or spin-spin) relaxation time distribution is used to infer pore-size information and to estimate permeability [1, 2]. The major methods used for estimating permeability, *k*, are the Schlumberger Doll Research (SDR) model and Timur-Coates (TC) model [3, 4]:

$$\text{SDR model: } k_{SDR} = a\phi_{NMR}^4 T_{2LM}^2 \text{ [mD]}$$

$$\text{TC model: } k_{TC} = c\phi_{NMR}^4 \left(\frac{FFV}{BFV}\right)^2 \text{ [mD]}$$

Where ϕ_{NMR} is the NMR-estimated (effective) porosity. SDR model uses the averaged value of the T_2 distribution plotted on log-scale of time and matches it to the experimental reference permeability with the fitting parameter *a* [mD/(ms)^2]. The TC model seeks to differentiate between the fraction of free (mobile) fluid volume (FFV) and bound fluid volume (BFV) and estimates permeability with FFV/BFV ratio and the material constant *c* [m^2/s^2]. The permeability in the research and development of methane hydrate, which is expected to be a next-generation resource, has been estimated using above methods. Methane hydrate is an ice-like solid crystalline structure of water and methane molecules. Because hydrate is solid, NMR is not sensitive, the initial (effective) permeability can be estimated by NMR analyzer. On the other hand, A strong disconnect (up to 2 orders of magnitude) between NMR-based estimates of permeability with those determined from a laboratory study of pressure cores from the same reservoir has further cast uncertainty in the application of borehole NMR data in hydrate evaluation [5, 6]. Recently, authors provided comparisons between NMR-derived values and direct fluid flow estimates of permeability in naturally occurring hydrate-bearing sediment [7, 8]. On the basis of the NMR measurement for hydrate-bearing pressure core sediments, which were recovered from the Gulf of Mexico and Alaska North Slope, the following new hydraulic radius model was proposed [7].

$$\text{Hydraulic radius model:} \quad k = C_s \phi_{NMR} \left(\frac{c_n \rho_2}{4 \sum \frac{f(T_{2i})}{T_{2i}}} \right)^2 \times 10^3 \quad \text{[mD]}$$

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This equation estimates the specific surface based on the NMR signal and has been shown to successfully estimate the initial permeability of a hydrate reservoir by expressing a hydraulic radius model based on Kozeny's equation [9]. However, the proposed equation is not universal and has been found to overestimate for clayey and silty hydrate free sediment. This study summarizes the methods and parameters used to estimate permeability using NMR signals from hydrate-bearing sediment obtained from logging and laboratory tests for the Gulf of Mexico and Alaska North Slope. In addition, we reports parameters for predicting model for muddy sediments which was recovered from overburden of hydrate-reservoir in the Hyuganada sea in 2022 Japan [10, 11]. When using the hydraulic radius model to predict permeability of hydrate-bearing sediment, reasonable estimates can be obtained by setting the shape factor for grains C_s = 1/2 (for a circular grain) and the shape factor for the flow path c_n = 4 (for the cylinder network), respectively. Although, for hydrate free muddy sediment, C_s = 1/3 for parallel plate grain shape and c_n = 2 for the fracture network model matched its permeability. Furthermore, the conversion parameter from T_2 relaxation time to the pore size for hydrate free muddy sediments ρ_2 = 0.009 (mm/s) was confirmed based on the result of mercury injection capillary pressure analysis, which is lower than ρ_2 = 0.0325 (mm/s) of hydrate-bearing sediments.

Contributor statement

Jun Yoneda designed the experiments, conducted permeability test with NMR, and analyzed the data and wrote the paper. *Kiyofumi Suzuki* designed a coring process and analyzed LWD data and established permeability predictions. *Yusuke Jin* contributed to the development of permeability testing apparatus and writing the paper.

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