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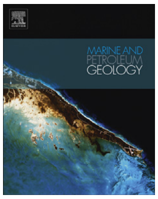

Research paper

Permeability of sediment cores from methane hydrate deposit in the Eastern Nankai Trough

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ABSTRACT

Effective and absolute permeability are among the most important factors affecting the productivity of hydrate-bearing sediments during gas recovery operations. In this study, effective and absolute permeability have been measured using natural sediment cores obtained from a methane hydrate reservoir in the Eastern Nankai Trough off the shore of Japan. The cores were recovered under pressure and shaped cylindrically with liquid nitrogen spray after rapid pressure release. The cylindrical core was inserted into a core holder for flooding tests in order to apply a near in situ effective stress. The effective permeability of water in the hydrate-bearing sandy sediment was 47 millidarcies (md) with a hydrate saturation of 70%. After hydrate dissociation, the absolute permeability was estimated to be 840 md. Other test results showed that the absolute permeability of the hydrate-free sediments was estimated to be tens of microdarcies for clayey sediments, tens of md for silty sediments, and up to 1.5 darcy for sandy sediments. Absolute permeability showed a strong correlation with sediment grain size in log–log plots. In addition, the effective permeability of hydrate-bearing sandy sediments and the absolute permeability of hydrate-free sandy sediments correlated with the effective porosity. We compared measured data to other experimental data using pressure cores recovered from the same well and wireline pressure tests from a well near the coring well. The results are consistent with each other. At this location, we found that the effective permeability for hydrate-bearing sandy sediments was in the range of 1–100 md, which was 2–3 orders of magnitude higher than conventional estimates. Finally, the change of permeability, potentially caused by depressurization-induced gas production, was analyzed. It was found that the high effective stress owing to depressurization and freshwater generation originating from hydrate dissociation caused reduction in absolute permeability.

1. Introduction

Natural gas hydrates are crystalline solids composed of water and guest molecules (Sloan and Koh, 2008). Methane hydrate is a gas hydrate in which predominantly methane molecules are trapped, and it is common in natural environments, such as permafrost regions and shallow sediments on marine continental margins. Recent studies show that hydrate-bearing sands are the most feasible energy resource targets for recovery of gas. The reason for the great resource potential of sand sediments is their greater intrinsic (absolute) permeability (Boswell and Collett, 2011). For economic gas recovery from hydrate-bearing sand sediments, initial effective

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permeability (initial water or gas permeability of hydrate-bearing sediments) is the most important factor because it directly affects the gas production rate and recovery factor. Konno et al. (2010a) numerically simulated the depressurization-induced gas production and concluded that the initial effective permeability of hydrate-bearing sediments is a crucial factor for successful gas production. They suggested that effective permeability higher than the threshold value is absolutely necessary for depressurization.

To date, experimental studies have evaluated the effective permeability of hydrate-bearing sediments using cores with synthetic methane hydrate (Kleinberg et al., 2003; Kneafsey et al., 2011b; Liang et al., 2011; Seol and Kneafsey, 2011; Konno et al., 2013) and CO_2 hydrate (Kumar et al., 2010). In order to characterize methane hydrate-bearing sediment, proton nuclear magnetic resonance (NMR) is applied to measure pore size distribution of unconsolidated sediment (e.g., Minagawa et al., 2008). Modeling has also been attempted to understand microscale flow mechanisms by accounting for gas invasion and gas nucleation processes (Jang and Santamarina, 2014) and hydrate pore-scale growth habit and meso-scale heterogeneity (Dai and Seol, 2014). Although cores with synthetic hydrate are widely used for permeability measurements, it is important to study naturally occurring hydrate-bearing sediment in actual reservoirs to ensure accurate evaluation of gas productivity.

For natural sediments, wireline logging has been widely used to estimate effective permeability. Combinable nuclear magnetic resonance (CMR) logging was conducted in the Eastern Nankai Trough, and the initial effective permeability of hydrate-bearing sediments was estimated to be in the range of 0.01–10 md (Uchida and Tsuji, 2004). At the Mount Elbert site on the Alaska North Slope, a formation pressure test was conducted to estimate initial effective permeability through numerical simulation (Anderson et al., 2011; Kurihara et al., 2011). Estimated initial effective permeability was in the range of 0.12–0.17 md. At the Mallik field on Mackenzie Delta, initial effective permeability in a highly hydrate-saturated sand layer was estimated to be lower than 1 md based on CMR logging (Fujii et al., 2012).

In contrast, a few experimental studies estimated the permeability of natural sediments in gas hydrate deposits. Jin et al. (2007) analyzed frozen hydrate-bearing sediments recovered from the Eastern Nankai Trough offshore of Japan using microfocus X-ray computed-tomography to investigate the flow channel structure. For the sediment core recovered from the same area, Konno et al. (2010b) conducted a numerical simulation analysis as part of a dissociation experiment and reported that initial effective water permeability was 3–4.8 md at a hydrate saturation of 52.0% for naturally occurring hydrate-bearing sediment. Sediment cores used in these studies were recovered using a Pressure Temperature Core Sampler (PTCS) in 2004 (Takahashi and Tsuji, 2005). In the permafrost region of Mount Elbert, Winters et al. (2011) measured intrinsic (absolute) permeability of sediment cores. However, the initial effective permeability could not be determined because the gas hydrate was already dissociated. To estimate effective and relative permeability (defined as the ratio of effective permeability and absolute permeability) of hydrate-bearing conditions, Johnson et al. (2011) artificially formed gas hydrate in sediment cores recovered from the Mount Elbert's permafrost region. To estimate effective permeability, Li et al. (2014) recently conducted NMR measurements in the laboratory using samples of hydrate-bearing sandstone recovered from the Shenhu area of the South China Sea.

Pressure coring systems, such as PTCS, are expected to be the most effective methods of core recovery for hydrate-bearing sediments. However, it is difficult to preserve hydrates from disturbance during the core handling process. This is because a pressure release process must be conducted in order to shape the cores and place them in a core holder for effective permeability studies. To estimate nearly in situ properties from these cores, it is important to understand the degree of disturbance. In this study, we investigated the effect of the pressure release process on the sample texture and the amount of remaining hydrates in the sediment cores recovered using the pressure coring system. By introducing an effective pressure release process, the effective water permeability of undisturbed hydrate-bearing sediments was determined. In addition, the results were compared to recent pressure core analyses and field logging data. This was possible because new cutting-edge analysis and transfer systems of pressure cores allow nondestructive (conducted without pressure release) analyses of hydrate-bearing sediments (Schultheiss et al., 2011; Santamarina et al., 2012). On the basis of a comparison with these studies, the effective permeability of the hydrate reservoir at this location is discussed in this paper. In addition, absolute permeability, which is the intrinsic permeability of the hydrate-free sediment, was analyzed for various sediment lithology in the hydrate deposit. Finally, the change of absolute permeability resulting from depressurization-induced gas production was analyzed.

2. Methods

2.1. General core information

Sediment cores were recovered from well AT1-C in the Eastern Nankai Trough off the shore of Japan. The coring operation was conducted during June–July 2012 using the Hybrid Pressure Coring System developed by the Japan Agency for Marine-Earth Science and Technology, Aumann and Associate Inc., and JOGMEC (Kubo et al., 2014; Inada and Yamamoto, 2015). During the coring operation, most of the cores were maintained within the hydrate phase stability P–T conditions. However, some of the cores were unexpectedly depressurized during core retrieval owing to mechanical problems. In this study, both of pressure-preserved and unpreserved cores were used for permeability measurements. The diameter of the recovered cores was 50.8 mm (2 in). The length of the cores, which depends on the recovery ratio, was up to 3 m. The exterior of the cores was covered by using a 3-mm-thick plastic liner with an inner diameter of 53.6 mm. The lithology of recovered cores indicated clayey, silty, and sandy layers of a turbidite reservoir. On the basis of the P-wave velocity measurement conducted under pressure, the pressure-preserved silty and sandy cores were determined to be methane-hydrate-bearing sediments (Suzuki et al., 2015). The pressure-preserved cores were stored in pressure vessels (storage chambers) with freshwater.

2.2. Sample preparation procedure

Before the permeability measurements, all cores were subjected to a liquid nitrogen (LN_2) treatment for the purpose of cylindrically shaping the test samples. The procedure was performed at atmospheric pressure after the pressure release of the pressure-preserved cores. The storage chamber of the pressure-preserved core was immersed in a cooling bath to minimize hydrate dissociation during the pressure release process. In this study, we followed two different cooling procedures: cooling in seawater and freezing in gas atmosphere. Most of the core storage chambers were immersed for 1 h in a cooling bath with salt and ice at -2 °C, which is the point at which seawater freezes. In this case, the pore space seawater was not frozen. One storage chamber was instead immersed in a cooling bath with brine solution overnight at approximately -4 °C to freeze the pore space seawater. Thus, the seawater and freshwater mixture in the storage chamber was replaced by methane gas at 8 MPa prior to freezing because the frozen water prevented the core recovery from the storage chamber