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Research paper

Effect of methane hydrate morphology on compressional wave velocity of sandy sediments: Analysis of pressure cores obtained in the Eastern Nankai Trough

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ABSTRACT

Sediment cores containing methane hydrate were obtained under pressure from the Eastern Nankai Trough offshore Japan, and they have been analyzed to investigate the relationship between compressional wave velocity (P-wave velocity), methane hydrate saturation, and pore space hydrate morphology. P-wave velocities of pressure cores were measured at near in-situ pressures, thus preventing hydrate dissociation. After the measurement of P-wave velocity, the cores were cut, under pressure, into separate P-wave velocity intervals. Each core interval was depressurized while measuring the evolved gas volume to quantify methane hydrate saturation. The results show that P-wave velocity correlates well with hydrate saturation; the P-wave velocity varied from less than 1700 m/s in the hydrate-free section to greater than 2300 m/s in the section with the highest hydrate saturation of 72%. The measured P-wave velocities were correctly reproduced by the sediment frame component model by adjusting model parameters such as sand-clay ratio and effective stress. It was found that all core data plotted within the model predictions assuming zero effective stress and assuming in situ effective stress. This may indicate that the cores were in the process of relaxing from their in situ effective stress at the time of measurement. By using pressure cores and pressure core analysis technology, the relationship between P-wave velocity and methane hydrate saturation has been directly obtained nondestructively. The observed relationship in high-resolution core-scale specimens enables estimation of the hydrate morphology and is expected to be more accurate than cross-plot data in well logging.

1. Introduction

Methane hydrate, which is a crystalline compound formed from methane and water, is found in arctic and marine continental margin sediments worldwide (Sloan and Koh, 2008). The P-wave velocity of hydrate-bearing sediments is higher than that of hydrate-free unconsolidated sediments (e.g., Yuan et al., 1996), and laboratory experiments have shown that there is a strong relationship between the P-wave velocity and hydrate saturation (e.g., Berge et al., 1999). Through the comparison with model predictions such as those of Dvorkin et al. (2000), it was found that this relationship depends on the hydrate morphology, such as grain coating, cementing, pore-filling, and sediment frame component (or load-bearing) within the pore space (M. Lee et al., 1996; Berge et al., 1999; Reister, 2003; Yun et al., 2005; Priest et al., 2009; J. Lee et al., 2010; Hu et al., 2010, Li et al., 2011; Best et al., 2013; Kim et al., 2013a). This suggests that the P-wave velocity obtained from logging and seismic surveys can be used to estimate the in situ

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hydrate saturation if the hydrate morphology in actual reservoirs is revealed. P-wave velocity changes during CH_4–CO_2 replacement in hydrates have also been studied to estimate the sediment stiffness (Espinoza and Santamarina, 2011; Liu et al., 2013). It is therefore important to understand the relationship between the P-wave velocity, hydrate saturation, and hydrate morphology because these properties are deeply linked to the physical properties of hydrate-bearing sediments, such as their permeability, thermal properties, electrical conductivity, and shear strength (Waite et al., 2009; Santamarina and Ruppel, 2010).

Quantitative detection of methane hydrate in natural sediments has been attempted over the years. Wood et al. (1994) analyzed seismic interval velocities at the Blake Ridge for quantitative detection of methane hydrate. Chand et al. (2004) compared P-wave velocities predicted by four models and field data from the Mallik field in the Mackenzie Delta and the Blake Ridge. At the Mallik field, Carcione and Gei (2004) estimated hydrate saturation from well logging data and vertical seismic profiles by assuming that the hydrate filled pore space (pore-filling). Dash and Spence (2011) estimated hydrate saturation at the northern Cascadia margin using P-wave and S-wave velocities. They concluded that the hydrate is distributed as part of the load-bearing matrix. For other areas, such as the Nankai Trough, Mount Elbert, the Krishna–Godavari basin, the Ulleung Basin, and the Shenhu area of the South China Sea, estimations of hydrate saturation have also been conducted (Inamori et al., 2010; Lee and Collett, 2011; Kim et al., 2013b; Shankar and Riedel, 2011; Lee and Collett, 2013; Wang et al., 2014). Hydrate morphology was estimated as load-bearing at the Nankai Trough, Mount Elbert, and the Krishna–Godavari basin, whereas it was estimated to be pore-filling at the Ulleung Basin. Winters et al. (2004) reported that the mildly-disturbed samples recovered from the 2L-38 well at the Mallik field are best modeled as part of the sediment frame (load-bearing).

Laboratory experiments using artificial cores have also provided insight into the relationship between P-wave velocity and hydrate saturation; however, there are some limitations to the use of artificial cores in estimating hydrate saturation in natural sediments. One of the reasons is that it is difficult to control hydrate morphology in such a way as to mimic natural features in artificial cores. Hydrate formed in a gas-rich environment, which is a conventional method used in laboratory studies, generally shows a cementing morphology (Winters et al., 2004; Priest et al., 2005, 2006). In contrast, hydrate formed from methane dissolved in the pore fluid, which is considered as common in natural environments, may not show a cementing morphology (Spangenberg et al., 2005, 2008; Winters et al., 2007). Using a non-methane hydrate former, Yun et al. (2005) and Lee et al. (2010) documented a transition between pore-filling and load-bearing hydrates at saturation of ~40%–50% of pore space.

Gas hydrate morphology in natural sediments is depends on the hydrate occurrence mechanism; however, it is difficult to know the occurrence mechanism for each reservoir. Analysis of logging data seems to be effective in estimating the actual relationship between P-wave velocity, hydrate saturation, and hydrate morphology in natural sediments. However, the spatial resolution of P-wave velocity data and hydrate saturation data, as estimated from resistivity logging, is larger than that of core data, and the various datasets are not usually entirely coincident. Thus, cross-plots of P-wave velocity and hydrate saturation are often so scattered that it is difficult to accurately constrain the hydrate morphology. In addition, the frequency used for in situ exploration is much lower than that used in laboratory experiments, which results in differences in the depth and spatial resolution of measurements. In situ exploration data are spatially-averaged and appropriate for the determination of the hydrate distribution in bulk sediments. However, such data are difficult to apply to the investigation of local properties, such as the pore space hydrate morphology. Consequently, high frequency laboratory experiments using natural sediments are more favorable for the analysis of pore space hydrate morphology.

Pressure core analysis technologies now enable the study of relatively undisturbed samples recovered from hydrate-bearing natural sediments, and pressure core analyses of P-wave velocities have been conducted for hydrate-bearing natural sediments (Yun et al., 2006, 2010, 2011; Schultheiss et al., 2011). Lee et al. (2013) successfully determined the relationship between P-wave velocity and hydrate saturation from pressure cores recovered from the Ulleung Basin. They concluded that the hydrate morphology is pore-filling at low hydrate saturations, but gradually deviates from pore-filling toward cementation as hydrate saturation increases, in accordance with studies of Yun et al. (2005) and Lee et al. (2010). They used the Pressure Core Analysis and Transfer System (PCATS) developed by Geotek Ltd. (Schultheiss et al., 2011) to measure P-wave velocity through the core liner at high resolution. However, the study noted that the data resolving hydrate saturation was much lower than that of P-wave velocity because hydrate saturation was calculated based on a dissociation experiment conducted on the whole core including both high and low P-wave velocity sections (Lee et al., 2013).

In this study, a newly developed pressure core cutting, manipulating, and analyzing system was used to overcome the discrepancy of data resolution between P-wave velocity and hydrate saturation. P-wave velocity was measured by the PCATS at a high resolution using pressure cores recovered from the Eastern Nankai Trough offshore Japan. After the P-wave velocity measurements, the cores were cut into pieces under pressure for separate P-wave velocity intervals on the basis of visual observation enabled by our pressure core system. To obtain high resolution hydrate-saturation data, each sub-sampled core was depressurized and the gas volume was measured. By comparing experimental data with physical model predictions, hydrate morphology in pore space was studied in detail.

2. Methods

2.1. Core samples

Hydrate-bearing cores were recovered from the AT1-C well, which penetrated in turbidite sand sediment in the Eastern Nankai Trough offshore Japan during June–July 2012 (Fujii et al., 2015). The Hybrid Pressure Coring System, developed by the Japan Agency for Marine-Earth Science and Technology, Aumann and Associate Inc., and JOGMEC, was used for the coring (Kubo et al., 2014; Inada and Yamamoto, 2015). The cores were maintained within the pressure and temperature (P–T) hydrate phase stability field during the coring operation (Suzuki et al., 2015). The diameter of the recovered core is 50.8 mm (2 inches). The length of the core, which depends on the recovery ratio, is up to 3 m in our operation. The periphery of the core was covered by a 3 mm-thick plastic liner with an inner diameter of 53.6 mm. The recovered cores were stored in pressure vessels (storage chambers) with fresh water.

2.2. Onboard operation: property scans, cutting, and transportation

The cores with plastic liners were handled aboard the ship using the PCATS, which was developed and operated by Geotek Ltd. (Schultheiss et al., 2011). To prevent hydrate dissociation, the operating pressure and temperature were kept at 20 MPa and 283.15 K, respectively. The cores were manipulated into a scanning section of PCATS to collect 2-D X-ray images, 3-D X-ray CT images, gamma density data, and P-wave velocity data (Suzuki et al., 2015).