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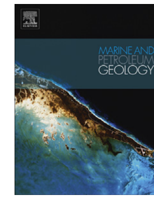

Research paper

Lithological features of hydrate-bearing sediments and their relationship with gas hydrate saturation in the eastern Nankai Trough, Japan

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A B S T R A C T

Gas hydrate-bearing sediments from the eastern Nankai Trough, Japan, are characterized in terms of their lithology, interpreted processes and paleoenvironments of deposition, and various geometric parameters of their grain size distribution. These data are used to determine the relative influence of each characteristic on gas hydrate saturation within the sedimentary column. Four lithologies have been identified in a single turbidite sequence that can be attributed to hyperpycnal flow deposits, Tc or Td divisions of a turbidite sequence, a Te division of a turbidite sequence, and hemipelagic mud. Facies association indicates that the sediment core can be vertically divided into units that are characteristic of three depositional environments: a lowermost channel-fill turbidite sequence, an intervening sheet-like turbidite sequence, and an uppermost basin floor sequence. The channel-fill turbidite and sheet-like turbidite sequences are the best hydrate reservoirs, as evidenced by the high levels of gas hydrate contained within them. The relationships between gas hydrate saturation and the grain size distribution parameters of median grain size, sand content, and skewness show that the latter can be useful tools with which to assess the quality of the gas hydrate reservoir in the eastern Nankai Trough area. This result provides useful criteria for assessing reservoir quality in the eastern Nankai Trough area.

1. Introduction

Gas hydrates are ice-like crystalline solids in which gas molecules are caged within a solid lattice of water molecules (Kvenvolden, 2000). These clathrate structures are only stable under high-pressure and low-temperature conditions, such that gas hydrates are restricted to regions of permafrost, high-latitude lakes, and oceanic margins (Ergov et al., 1999). Many recent studies have attempted to characterize the properties of gas hydrate-bearing sediments in marine environments, including those from the Nankai Trough, offshore Japan (e.g., Uchida et al., 2004; Fujii et al., 2008, 2009, 2013), the Ulleung Basin, offshore Korea (e.g., Kim et al., 2011; Bahk et al., 2011, 2013; Kwon et al., 2011), the Cascadia margin (e.g., Riedel et al., 2009; Trehu et al., 2004; Torres et al., 2008), the Gulf of Mexico (Winters et al., 2008; Boswell et al., 2012; Collett et al., 2012), the Alaska North Slope (e.g., Rose et al., 2011; Winters et al., 2011), the South China Sea (e.g., Yun et al., 2006; Wang et al., 2011), and offshore of India (e.g., Collett et al., 2014; Kumar et al., 2014; Winters et al., 2014; Rose et al., 2014). Developing safe technologies that will allow the production of natural gas from such gas hydrate-bearing sediments is an important area of current scientific research, as gas hydrates are thought to be a potential energy resource for the 21st century.

The eastern Nankai Trough was selected as the site at which to test for gas hydrate production (Fujii et al., 2008; Yamamoto et al., 2010). Seismic surveys have identified the presence of a bottom-simulating reflector (BSR) that often appears at the base of a gas

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hydrate reservoir (Ashi et al., 2002; Hayashi et al., 2010). Furthermore, seismic reflection patterns and their shapes have indicated that the gas hydrate reservoir occurs as several channel deposits in a deep submarine-fan system (Arato and Takano, 1995; Takano et al., 2009; Noguchi et al., 2011). Studies of sediment cores have revealed that gas hydrate mostly assumes a pore-filling morphology in unconsolidated sands, although some occurs in a nodular form in the eastern Nankai Trough region (Tsuji et al., 2004; Uchida and Tsuji, 2004; Uchida et al., 2004; Fujii et al., 2009). Previous studies have documented the role of sand content and median grain size in gas hydrate distribution by demonstrating that gas hydrate selectively accumulates in coarse-grained sediments (Ginsburg et al., 2000; Uchida et al., 2004; Torres et al., 2008; Fujii et al., 2009; Dugan and Daigle, 2011; Winters et al., 2011; Bahk et al., 2011; Winters et al., 2014). However, those studies focused specifically on the sand content and median grain size of sediments and did not fully consider the influence of other geometric parameters of grain size distribution such as skewness, sorting, and kurtosis (Folk and Ward, 1957). The purpose of this study is to identify the lithological features of gas hydrate-bearing sediments that were recovered from the eastern Nankai Trough during a pressure coring campaign run by the Research Consortium for Methane Hydrate Resources in Japan (MH21). We have also performed detailed investigations into the role of different geometric parameters of grain size distribution throughout the sediment core as related to varying gas hydrate content.

2. Geological and geophysical setting

The Nankai Trough is an active convergent plate margin where the Philippine Sea Plate is undergoing northwest-directed subduction beneath the Eurasian Plate. Our study considers gas hydrate deposits that have been documented in the Kumano forearc basin region of the eastern Nankai Trough (Fig. 1) (Tsuji et al., 2004; Uchida and Tsuji, 2004; Uchida et al., 2004; Fujii et al., 2009). A zone with concentrated methane hydrate, several tens of meters in thickness, was discovered during the drilling of a well in 2004 (Fujii et al., 2009). Most of the methane gas recovered by the well is of microbial origin (Uchida et al., 2009).

At the study site, Quaternary sediments overlie the gas hydrate-bearing Plio–Pleistocene Kakegawa and Ogasa Groups (Hiroki et al., 2004; Arai et al., 2006; Takano et al., 2009). Seismic sequence stratigraphy has indicated that the Kakegawa and Ogasa Groups can be vertically divided into 17 depositional sequences, Kg–a to Kg–h and Og–a to Og–i, in ascending order (Noguchi et al., 2011). Moreover, seismic facies features have shown that the depositional environment was that of a deep submarine-fan system (Takano et al., 2009).

This submarine-fan system is thought to have changed from initially being dominated by braided rivers to being dominated by a channel-levee system during the Plio–Pleistocene (Takano et al., 2009; Noguchi et al., 2011). In the late Pliocene Kakegawa Group, the sequence intervals between Kg–a and Kg–c can be categorized as braided river submarine fans, and those between Kg–d and Kg–h as small radial fan-type submarine fans. In the Ogasa Group, the early to middle Pleistocene intervals between Og–a and Og–f can be categorized as trough-filled small radial fan-type submarine fans, and the late Pleistocene intervals between Og–h and Og–i can be interpreted as channel-levee dominated submarine fans. This study focuses on the depositional sequence between Og–b and the early stage of Og–c (Fig. 1).

In the eastern Nankai Trough area, the BSR and overlying high-amplitude seismic reflectors have been reported to produce large acoustic impedance contrasts due to elastic changes between the gas hydrate-bearing sediments and those containing no gas hydrate (Ashi et al., 2002; Hayashi et al., 2010). At the study site, it is well known that the BSR is indicative of the lower base of the gas-hydrate stability zone, while the high-amplitude reflectors above the BSR indicate the top of the gas-hydrate concentrated zone (Tsuji et al., 2004; Noguchi et al., 2011). Because both reflectors occur in the coring interval, the depositional sequence examined in this study corresponds to the zone of gas hydrate concentration.

3. Materials and methods

3.1. Coring operations and cores

About 60 m of gas hydrate-bearing sediment cores was acquired by a Hybrid pressure core sampler (Hybrid PCS) at the AT-1 well during the 2012 JOGEMC/JAPEX Pressure coring operation using D/V Chikyu (Yamamoto, 2015; Inada and Yamamoto, 2015). The sediment core was recovered between 260 and 320 m below sea floor (mbsf). Overall core recovery efficiency was 61%. In the AT-1 well, the coring well (AT1-C well: water depth of 988.7 m) and the monitoring well (AT1-MC well: water depth of 997.7 m), which produced geophysical well logs, are separated by a horizontal distance of ~40 m at the sea floor (Fujii et al., 2013).

Once the pressure cores were retrieved, they were immediately transferred into a Pressure Core Analysis and Transfer System (PCATS) to perform non-destructive tests such as X-ray imaging and *P*-wave velocity and gamma-ray measurements (Schultheiss et al., 2011). Afterwards, the sediment core was cut in PCATS transferred under pressure into 0.3-m- or 1.2-m-long storage chambers, and stored at a pressure of ~15 MPa and temperature of ~5 °C. Although depressurized cores are unsuitable for measuring the physical properties of hydrate-bearing sediments (e.g., Waite et al., 2008; Santamarina et al., 2012), the sediment characteristics do not change. Hence, a subset of the pressure cores was depressurized and stored in liquid nitrogen for analysis of various sediment characteristics.

A conventional coring tool, the Extended Shoe Coring System, was used alongside the Hybrid PCS coring. Those conventional cores were depressurized onboard. The sediment core was split into halves, the split core was photographed, and its lithology was described. One of the halves was subsampled for the purposes of sedimentological, geochemical, and microbiological analysis, and the other was placed in a long plastic case and imaged using X-ray computed tomography.

Subsamples of both pressure and conventional cores were used for grain size analysis to characterize the properties of the gas hydrate-bearing sediment. The horizons observed in the sediment core correspond to the seismic depositional sequence Og–b to early stage Og–c in the early to middle Pleistocene deposits (Noguchi et al., 2011) (Fig. 1).

3.2. Grain size measurements

Samples weighing ~100 mg were placed in a 50-ml capacity centrifugal tube and treated with 30% hydrogen peroxide (H_2O_2) for a week at room temperature in order to remove organic matter. Subsequently, 0.4% sodium diphosphate decahydrate solution ($Na_4P_2O_7 - 10H_2O$) was added as a dispersing agent. The grain size analysis was performed at average intervals of 17.3 cm using sliced core samples of length 5.4–15.5 cm. The residue was then analyzed with a Microtrac MT3300 EX (Nikkiso Co. Ltd.) laser-diffraction particle size analyzer, which can detect sediment grains in the size range 0.02–2000 μm, and results were expressed as volume percentages. The mechanical reproducibility was better than ±1% for the median grain size. The following geometric parameters