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Assessment of gas hydrate saturation in marine sediments from resistivity and compressional-wave velocity log measurements in the Mahanadi Basin, India

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ABSTRACT

Gas hydrate was recovered in the Mahanadi Basin along the eastern continental margin of India during the India National Gas Hydrate Program (NGHP) Expedition-01 in 2006. Infrared imaging of recovered core confirmed gas hydrate occurs predominantly in discrete layers. Pore-water chemistry, electrical resistivity and acoustic velocity down-hole logs were used to estimate gas hydrate saturations at three of the sites in the Mahanadi Basin: Sites NGHP-01-08, -09, and -19. Gas hydrate saturation estimated from pore-water chloride concentrations shows values up to ~10% of the pore space at ~200 m below seafloor just above the base of the gas hydrate stability zone (BGHSZ). Gas hydrate saturations estimated from electrical resistivity and acoustic velocity logs using standard relations and modeling approaches are comparable to each other and saturations are ~10–15% of the pore space. Seismic reflection data were also analyzed for the evidence of gas hydrate, and a bottom-simulating reflector (BSR) was imaged along the seismic profiles in the study area. The depth of the BSR is varying from ~200 m to ~300 m below seafloor depending on water depth in the Mahanadi Basin. The occurrence of gas hydrate was observed to be associated with deep-water channel and levee complexes (especially at Site NGHP-01-19) based on the regional seismic data. But the cored/logged section at each site lacked any significant sand fraction, which does not allow for higher gas hydrate saturations. As identified from seismic time-slice data, all sites drilled in the Mahanadi Basin are within the steeper slope region of the channel system and any sand bypassed this region. Significant sand deposition would occur further down slope where typical fan-type deposits can be inferred from the seismic data and thus higher accumulations of gas hydrate would be expected.

1. Introduction

Gas hydrates are solid crystalline, ice like substances consisting of a methane molecule surrounded by a cage of water molecules. The large amount of methane stored as gas hydrates in marine sediments is considered an unconventional potential future energy resource due to their worldwide abundance (Kvenvolden and Barnard, 1983; Sloan, 2003; Sloan and Koh, 2008). Marine gas hydrate generally occurs within the top few hundred meters of sediments in continental margins (e.g. Kvenvolden et al., 1993). The inclusion of gas hydrate in marine sediments usually changes the physical properties of the bulk sediment. Gas hydrate can take on many physical forms, including small nodules, lenses, veins, fracture-filling, and pore-filling. In the simplest model, methane combines with the sediment pore water to form gas hydrate, partially replacing the pore fluid, but with little change to the sediment structure. More complex models involve gas hydrate crystal growth by displacement of the surrounding sediments, in form of veins, fracture-fill, small nodules, or lenses.

The presence of gas hydrate in marine sediments can therefore significantly affect the bulk physical properties of the sediments. Gas hydrates exhibit relatively high compressional-wave velocity (V_p) compared to pore-filling fluids such as water; therefore, the velocity of gas hydrate-bearing sediments is usually elevated (Stoll et al., 1971; Tucholke et al., 1977). Seismic velocities can be obtained from multi-channel seismic data, down-hole wire-line, and logging-while-drilling (LWD) sonic logs, or vertical seismic profile (VSP) measurements (Westbrook et al., 1994; Yuan et al., 1996;

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Paull et al., 1996). Numerous studies have attempted to relate seismic velocity to gas hydrate saturation, using a variety of approaches. Most methods can be classified as empirical porosity–velocity relations applied to effective porosity reduction models (e.g. Hyndman et al., 1993; Yuan et al., 1996), time-averaging approaches (e.g. Pearson et al., 1983; Lee et al., 1993), and first-principles-based rock-physics modeling approaches (e.g. Dvorkin and Nur, 1993; Carcione and Tinivella, 2000; Helgerud et al., 1999; Dai et al., 2008).

From the various physical-property down-hole logs, resistivity appears to be the most strongly affected by the presence of gas hydrate in the marine sediment. Its inclusion in the pore space of marine sediments can significantly affect the bulk electrical properties of the sediment. The measurement of such properties can therefore be used to estimate gas hydrate saturation (e.g. Collett and Ladd, 2000; Yuan et al., 1996; Shankar and Riedel, 2011; Wang et al., 2011). Natural gas hydrate formation reduces the effective porosity and electric conductivity, so that gas hydrate-bearing sediments exhibit higher electrical resistivity in comparison to water-saturated sediment. Down-hole resistivity logs have been used extensively to characterize the in-situ properties of gas hydrate-bearing sediments and estimation of gas hydrate saturations (e.g. Collett and Ladd, 2000; Guerin et al., 1999; Helgerud et al., 1999; Hyndman et al., 1999, 2001; Lee and Collett, 2005; Lee and Waite, 2008; Shankar and Riedel, 2011; Wang et al., 2011).

The presence of gas hydrate in the Mahanadi (MN) Basin, on the eastern continental margin of India, was inferred based on studies of seismic, well-log, and core data (Collett et al., 2008, 2014; Prakash et al., 2010). Several geophysical investigations (Bastia, 2006; Bastia et al., 2010a,b; Prakash et al., 2010) in the MN Basin have been carried out to study the hydrocarbon prospect and gas hydrates. Using multi-channel seismic data along the MN Basin, wide-spread bottom-simulating reflectors (BSRs) have been identified and used to infer the presence of gas hydrate (e.g. Prakash et al., 2010). High reflection amplitude BSRs, and high seismic reflectivity below BSRs may be due to the presence of free gas were observed in the central part of the basin. Additional 3D seismic data were analyzed for BSRs and seismic proxies related to the presence of natural gas hydrate in the Mahanadi Basin by Prakash et al. (2010). This analysis shows the presence of BSRs and BSR-like features over a large area of nearly 250 km^2 in the central western part of the basin.

The NGHP Expedition-01 was designed to conduct scientific ocean drilling, coring, logging, and geologic studies to assess the regional geologic context and characteristics of gas hydrate occurrences along the continental margins of India (Collett et al., 2008, 2014). Drilling was performed with the *D*/*V* JOIDES Resolution. During the India NGHP Expedition-01, 21 sites were drilled in total. Out of these 21 sites, four were located in the MN Basin (Fig. 1). Following a logging-while-drilling/measurement while drilling (LWD/MWD) leg (Sites NGHP-01-08 and -09 in Mahanadi), down-hole continuous coring and pressure cores were acquired to recover gas hydrate samples in Mahanadi at Sites NGHP-01-18, and -19. After the coring program was completed at each site, wire-line logging was performed to acquire geophysical data for gas hydrate characterization. Site NGHP-01-18 was the first site cored and drilled in Mahanadi after the LWD/MWD program at Sites NGHP-01-08 and -09. At Site NGHP-01-18, one hole (NGHP-01-18A) was drilled and cored to a depth of 190 m below seafloor (mbsf). Pressure coring and wire-line logging were not attempted due to severe weather conditions (Collett et al., 2008, 2014). Hole NGHP-01-18A was truncated at ~210 mbsf, which is ~20 m above the top of the seismically inferred free gas-bearing section. Site NGHP-01-19 was the second site cored in the Mahanadi Basin. Site NGHP-01-19 was drilled in a seismically-imaged gap between two similar channelized free gas accumulations in order to safely obtain core and down-hole log data from both above and below the expected base of the gas hydrate stability zone (Collett et al., 2008, 2014). At site NGHP-01-19, two holes (NGHP-01-19A and -19B) around 10 m apart were drilled and cored. Hole NGHP-01-19A was cored to a depth of 305 mbsf (with conventional and pressure cores). Three successful pressure cores were recovered at 128 mbsf and 195.3 mbsf respectively at whole NGHP-01-19A. Hole NGHP-01-19B was drilled (partially cored) and wire-line logged to 280 mbsf and a Vertical Seismic Profile survey was conducted.

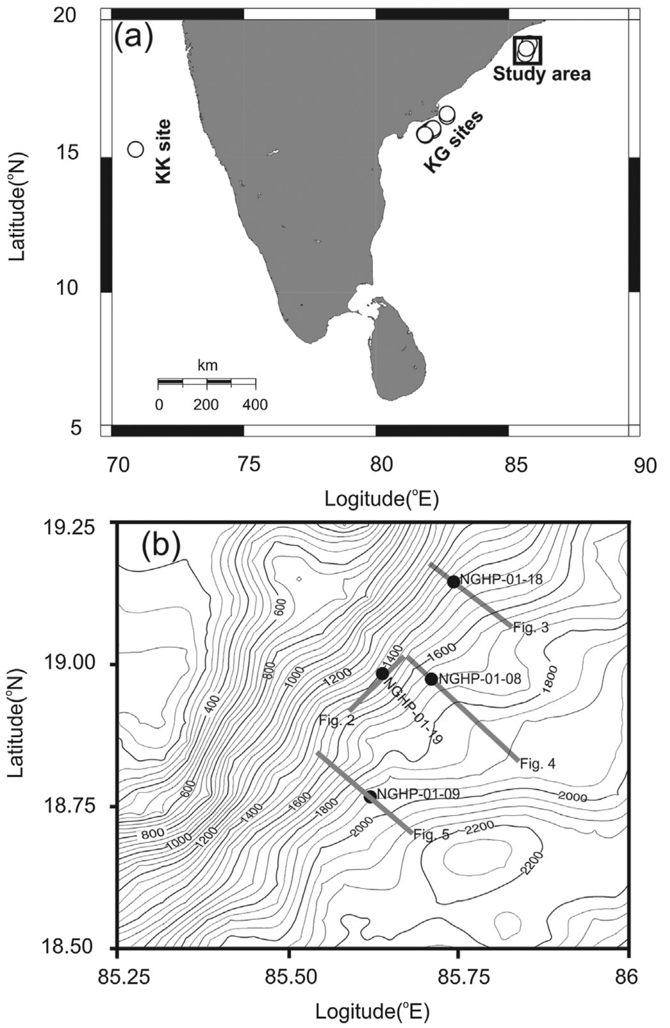

Figure 1. (a) Map of study area showing the location of the drilling Sites NGHP-01-08, -09, -18, and -19 in the Mahanadi Basin drilled during NGHP Expedition-01 and (b) Detail bathymetry of study area with drill site location (black filled circle). The bold solid lines mark the transect of the seismic lines, which are crossing or adjacent to the drilling sites shown.

In this study we present the first detailed gas hydrate characterization of the MN Basin based on seismic and borehole geophysical data. Our main objectives are to calculate gas hydrate saturations utilizing borehole data from MN sites using electrical resistivity log data, acoustic modeling methods of acoustic log data, and core-derived pore-water chlorinity freshening trends.

2. Geological setting

The MN Basin is a major sedimentary basin located along the east coast of India and extends from Jagannathpur in the north to