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Gas hydrate identified in sand-rich inferred sedimentary section using downhole logging and seismic data in Shenhu area, South China Sea

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A R T I C L E I N F O

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A B S T R A C T

Downhole wireline log (DWL) data was acquired from eight drill sites during China's first gas hydrate drilling expedition (GMGS-1) in 2007. Initial analyses of the acquired well log data suggested that there were no significant gas hydrate occurrences at Site SH4. However, the re-examination of the DWL data from Site SH4 indicated that there are two intervals of high resistivity, which could be indicative of gas hydrate. One interval of high resistivity at depth of 171–175 m below seafloor (mbsf) is associated with a high compressional- wave (P-wave) velocities and low gamma ray log values, which suggests the presence of gas hydrate in a potentially sand-rich (low clay content) sedimentary section. The second high resistivity interval at depth of 175–180 mbsf is associated with low P-wave velocities and low gamma values, which suggests the presence of free gas in a potentially sand-rich (low clay content) sedimentary section. Because the occurrence of free gas is much shallower than the expected from the regional depth of the bottom simulating reflector (BSR), the free gas could be from the dissociation of gas hydrate during drilling or there may be a local anomaly in the depth to the base of the gas hydrate stability zone. In order to determine whether the low P-wave velocity with high resistivity is caused by in-situ free gas or dissociated free gas from the gas hydrate, the surface seismic data were also used in this analysis. The log analysis incorporating the surface seismic data through the construction of synthetic seismograms using various models indicated the presence of free gas directly in contact with an overlying gas hydrate-bearing section. The occurrence of the anomalous base of gas hydrate stability at Site SH4 could be caused by a local heat flow conditions. This paper documents the first observation of gas hydrate in what is believed to be a sand-rich sediment in Shenhu area of the South China Sea.

1. Introduction

In April through June of 2007, the Expedition GMGS-1 was successfully completed in the Shenhu area of the South China Sea. Gas hydrate was detected at three (Sites SH2, SH3 and SH7) of the five sites that were cored. The gas hydrate host sediments at Sites SH2, SH3 and SH7 were predominantly silty-clays along with notable occurrence of foraminifera. At these sites, the gas hydrate-bearing sediment layers are about 10–25 m thick and lie just above the base of the predicted gas hydrate stability zone (BGHSZ) (Yang et al., 2008; Zhang et al., 2007; Chen et al., 2011; Liu et al., 2012; Lu et al., 2008; Wang et al., 2010; Wang et al., 2011a, b; Wang et al., 2012; Wu et al., 2011). The holes were not continuously cored because of the limited duration of the expedition. At Site SH2, gas hydrate was found at 195–220 m below seafloor (mbsf) and the average gas hydrate saturation in this interval was about 25% of the pore space with a maximum value of 47% (Wang et al., 2011b; Zhang et al., 2007). At Site SH3, gas hydrate was found in depth of 190–200 mbsf with a maximum gas hydrate saturation of 25% of the pore space calculated from pore-water freshening and the resistivity well log data (Wang et al., 2012). At Site SH7, a 25-m-thick layer of gas hydrate-bearing sediment was found at 155–180 mbsf and had a maximum saturation of 44% of the pore space (Yang et al., 2008; Wang et al., 2011a). Both the logging data and cores indicate that gas hydrate exists as pore filling material in mostly muddy sediments. The remaining cored sites (SH1 and SH5) showed no evidence for gas hydrate from pressure cores degassing or logging data. Although there is a thin layer (less than 1 m) with increased compressional-wave (P-wave) velocity and resistivity above the base of gas hydrate stability in the SH5 well, we cannot confirm the

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presence of gas hydrate due to lack of density log data. The remaining Sites SH6, SH9 and SH4 were not cored because of the apparent lack of evidence of gas hydrate from log data acquired at each site.

The grain size analysis of the sediments cored at Sites SH2 and SH7 show that higher gas hydrate saturations are associated with slight changes in sediment grain size and the occurrence of foraminifera (silt size particles), which provided the porosity required for the nucleation and formation of gas hydrates (Chen et al., 2011). It has been shown in other geologic settings that sediment grain size is an important factor controlling gas hydrate saturations, with coarse-grained sediments often exhibiting higher gas hydrate saturations (i.e., Boswell et al., 2012a; Collett et al., 2009; Torres et al., 2008; Tréhu et al., 2006).

Most of the gas hydrate-bearing sediments identified in the Nankai Trough (Japan) are associated with bottom simulating reflectors (BSRs), with the occurrence of pore-filling gas hydrates in turbidite sands that were deposited in distributary channels or distal lobes within a submarine fan system (Fujii et al., 2009). The primary objective of the Chevron-led Gulf of Mexico Gas Hydrate Joint Industry Project (GOM JIP leg II) was to confirm the occurrence of gas hydrate at high saturation in sand reservoirs as inferred from seismic studies (Boswell et al., 2009, 2012a, b; Collett et al., 2012; Frye et al., 2012; Hutchinson et al., 2008; Shelander et al., 2012; Zhang et al., 2012). From the sites drilled during the GOM JIP Leg II, the average gas hydrate saturations derived from resistivity and acoustic logs within the drilled sand layers ranged from about 50% to 80% of the pore space (Boswell et al., 2012a; Collett et al., 2012; Lee and Collett, 2012). In the Ulleung Basin Gas Hydrate Drilling Expeditions (UBGH 1 and UBGH 2), gas hydrate occurred either as a pore-filling type within discrete turbidite sand and ash layers, or as fracture-filling veins and nodules in hemipelagic mud, particularly in seismic inferred chimney structures (Bahk et al., 2011, 2013; Kim et al., 2013; Lee and Collett, 2013). Although gas hydrates in sand reservoirs have been found in many places, the only confirmed gas hydrates in the Shenhu area, SCS were in silt–clay dominated sediments as inferred from analysis of well log and cores acquired during GMGS-1.

As part of this study, we analyzed the well log data acquired in GMGS-1 by combining the logging data and surface seismic data to characterize the potential occurrence gas hydrate and free gas at Site SH4 in the depth between 170 and 180 mbsf. The main objective of this paper is to document the occurrence of hydrate-bearing sand-rich reservoirs in the SCS and to demonstrate how to identify gas hydrate and free gas reservoirs from well logs that have been degraded by enlarged borehole conditions by applying various rock physics models and attributes from surface seismic data.

2. Geological setting and data

The gas hydrate expedition GMGS-1 was conducted in the Baiyun Sag, Pearl River Mouth Basin (PRMB) of the northern slope of the South China Sea (SCS) (Fig. 1a). The PRMB lies in the central part of the northern SCS and occupies an area of 1.75×10^5 km^2. Gas hydrate exploration drilling was undertaken in the south- central region of PRMB, at a water depth of 1000–1300 m. Seventeen perpendicular-to-the-coast migrating submarine canyons have been identified in this basin, which have been migrating northeastward (NE) from the middle Miocene to present (Zhu et al., 2010; Ding et al., 2013; Li et al., 2013). Seven of the migrating canyons are located at the Baiyun Sag, with an additional ten in the Liwan sag. These canyons display both asymmetrical V- and U-shapes along their lengths. Numerous buried channels can be identified below the modern canyons with unidirectional

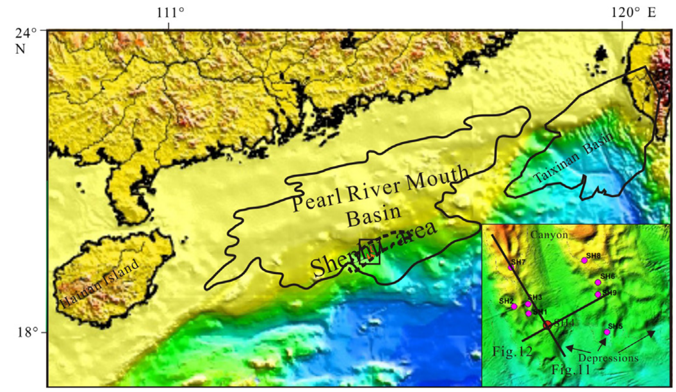

Figure 1. Location map showing the area of gas hydrate exploration in the Pearl River Mouth Basin, the northern South China Sea. The swath bathymetry highlights seafloor morphology of the sites drilled in this area and reveals the depressions and submarine canyons (Inset).

migration stacking patterns (Ding et al., 2013). Reflections within the canyons display a complex architecture indicating an evolution of repeated erosion, infilling, offset, and subsequent re-excavation. Each cycle of deposition in the canyon is marked by a basal erosional discontinuity (BED). Subsequently, erosional relief is partially filled by canyon thalweg deposits. The thalweg deposits are overlain by a lateral inclined package (LIP) and are marked by lens-shaped, parallel, high amplitude, continuous reflections that onlap basal erosional discontinuities. Canyon margin deposits consist of continuous reflections with high amplitude, and truncated by basal erosional discontinuities (Zhu et al., 2010). Many asymmetric scour-shaped depressions and crescent-shaped sediment waves were identified from the multibeam submarine geomorphology. Site SH4 was located at water depth of ~1289 m on the flank of a migrating canyon system (Fig. 1).

The borehole wireline log data acquired with Fugro logging-tools at Site SH4 include natural gamma, gamma density, electrical resistivity, fluid temperature, and sonic velocity (P-wave velocities). There were long and short spaced density log data acquired at Site SH4. The density logs have similar trends above the depth 175 m. However, the long spacing density data differs from the short spacing density data below 175 m. We used the long spaced density data because it measures deeper into the formation. The log data (especially P-wave velocity) was affected by changes of

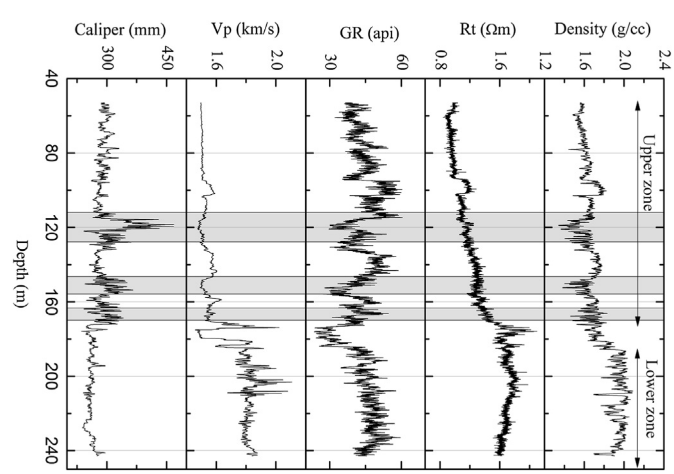

Figure 2. The downhole wireline logging (DWL) data from Site SH4 showing the three washout zones of degraded borehole conditions (gray zones).