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Research paper

Geophysical characterization of a fine-grained gas hydrate reservoir in the Shenhu area, northern South China Sea: Integration of seismic data and downhole logs

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ABSTRACT

High concentrated gas hydrate deposits in fine-grained sediment are proved to be eligible for exploitation with the current technology. Nevertheless, new insights and more understandings of the accumulation of gas hydrate and characterization of hydrate reservoir in fine-grained sediment are required, which can facilitate the commercial production of gas hydrate in the future. Combining seismic data and downhole logs, here we investigate a fine-grained gas hydrate reservoir in the Shenhu area, northern South China Sea (SCS). Gas hydrate with saturations of 10–45% occurs in fine-grained sediment. Besides the typical bottom-simulating reflectors (BSRs) and high amplitude reflection below BSR, a high amplitude positive reflector (referred to as the top of gas hydrate reservoir reflector; TGHR) exists at the top of high concentrated fine-grained gas hydrate reservoir. According to the result of acoustic impedance inversion, the TGHR is considered to represent a transitional zone from the overlying water-saturated sediment to the underlying high concentrated gas hydrate occurrence zone (GHOZ). Discontinuous BSRs beneath the traditional BSRs are also discovered in the study area, which are interpreted as the seismic evidence of the SII gas hydrate. In the Shenhu area, fluid flow features (such as chimney structures and faults) are found on the ridges where gas hydrate occurs, indicating that gas migration plays a critical role in the formation of gas hydrate in the fine-grained sediment. Our results provide valuable geophysical indications for detecting the presence of gas hydrate in fine-grained sediments.

1. Introduction

Gas hydrate is an ice-like compound formed from gas, mostly methane, trapped within a lattice of water molecules (Sloan, 1998). Hydrates are stable only within a narrow range of pressure and temperature, which exists in some marine and arctic areas within a limited depth range that is known as the gas hydrate stability zone (GHSZ). Gas hydrate sequesters a large amount of methane (Kvenvolden, 1988) and therefore it's a potential source of energy in the future. Many countries, such as Japan, India and the US, make national gas hydrate research plans and put forward the study of gas hydrate towards the ultimate objective, i.e. exploitation of gas hydrate economically and environment-friendly. Geophysical surveys and field drillings have confirmed the presence of gas hydrate in the shallow silt/shale sediments of the northern South China Sea (SCS) (Yang et al., 2008; Zhang et al., 2007). In 2017, Guangzhou Marine Geological Survey (GMGS) conducted the first methane production test from hydrate-bearing silt/shale sediments successfully in the Shenhu area, which demonstrates that gas hydrate can be extracted from marine fine-grained sediments using the current production technology. Thus, more work is needed to better understand the accumulation of gas hydrate and the characteristic of hydrate reservoir in fine-grained sediment, which can facilitate the commercial production of gas hydrate in the future.

The "gas hydrate petroleum system" concept was proposed to instruct the exploration of gas hydrate (Hutchinson et al., 2008; Jones et al., 2008). This approach considers the geologic factors and processes necessary to accumulate and preserve the gas hydrate, emphasizing the importance of availability of gas and water within GHSZ, and the function of reservoir rocks with sufficient porosity and permeability (Collett et al., 2009). With this concept as guidance, Joint Industry Project Leg II (JIP II) discovers high-concentrated gas hydrate (up to 80% of pore space) within channel-levee coarse-grained sediment in

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Lease Block GC955 and WR313, northern of Gulf of Mexico (Boswell et al., 2012a; Collett et al., 2012). The successful application of the "gas-hydrate petroleum system" concept is based on pre-drill precise processing and elaborate interpretation of seismic data (Hutchinson et al., 2008). The characteristic of gas hydrate deposits in the Shenhu area is quite different from those identified in GC955 and WR313. However, some of the ideas, such as the method of geophysical identification and quantification, and the "gas-hydrate petroleum system", could be applied to characterize the gas hydrate accumulation and reservoir properties in the fine-grained sediment of the SCS (Wang et al., 2014b).

Seismic data and well log data are widely used to study the gas hydrate occurrence, to describe the properties of the reservoir quantitatively and to infer the evolution of gas hydrate system. The bottom simulating reflector (BSR), which is a seismic marker at the base of the GHSZ, serves as a common proxy for the presence of hydrates, but BSR does not have a causative relationship with hydrate. Gas hydrate has been recovered where BSRs have been shown to be either present or absent (Holkrook et al., 1996; Hyndman and Spence, 1992). Numerous authors have reported that BSR is caused not by gas hydrate above but is due to free gas below (Shedd et al., 2012; Singh et al., 1993; Wang et al., 2014a). Besides, continuous, discontinuous, and pluming BSRs were proposed to indicate distinct gas hydrate systems (Shedd et al., 2012). In addition to seismic markers based on the configuration of reflectors, various theoretical and semi-empirical models are proposed to evaluate the gas hydrate reservoir quantitatively, such as those of Wood et al. (1994), the effective medium theory (Helgerud et al., 1999), the three-phase Biot-Type equation (Carcione and Tinivella, 2000; Lee, 2007). Full waveform inversion is used to calculate P-velocity in the Gulf of Mexico and estimate the gas hydrate saturation before drilling (Dai et al., 2008). The acoustic impedance of seismic data inverted using constrained sparse spike inversion serves to estimate the gas hydrate saturation in the Blake Ridge (Lu and McMechan, 2002) and the SCS (Wang et al., 2011). The acoustic impedance inversion of 3D seismic data, log to seismic tie and seismic attribute analyses were integrated to delineate gas hydrate occurrence in the Mallik site (Riedel et al., 2009).

Here, we examine a gas hydrate deposit through a comprehensive interpretation and a quantitative assessment by combining the seismic data and downhole logs in the northern SCS, in order to obtain some new insights into the reservoir properties in fine-grained sediments and the evolution of the gas hydrate accumulation. The paper is organized as follows: first, the gas hydrate occurrence is identified based on the combination of the drilling and the acoustic impedance inverted from seismic profile; then, we study the seismic characteristic of the gas hydrate occurrence zone in fine-grained sediment; in the end, we discuss the distribution of gas hydrate in this region and analyze distinct gas hydrate systems in fine-grained sediment of the study area.

2. Background

The SCS has developed on the proto-South China continental margin with intensive continental rifting from the latest Cretaceous and sea floor spreading since the late Oligocene to the mid-Miocene (Taylor and Hayes, 1983). As a result of the tectonic extension, a series of major Cenozoic rift basins, e.g., the Qiongdongnan Basin (QB), the Pearl River Mouth Basin (PRMB) and the Taixinan Basin (TB), have been formed in the northern margin of the SCS (Fig. 1) and several others in the southern margin. Given huge thickness of sediments, and plenty of organic matter input from South China continent and adjacent islands, the areas with a water depth greater than 500 m in the basins of northern SCS have become the target for the gas hydrate surveys (Wang et al., 2018).

In 2007–2016, GMGS conducted four gas hydrate drilling expeditions on the northern margin of SCS, validating the presence of gas hydrate in Pearl River Mouth Basin (PRMB), Taixinan Basin (TB) and Qiongdongnan Basin (QB) (Sha et al., 2015; Yang et al., 2008, 2015, 2017b; Zhang and Liang, 2015; Zhang et al., 2007) (Fig. 1a). In PRMB, gas hydrate is mainly identified within a submarine canyon development area on the continent slope in the Shenhu area (Fig. 1b). From the middle Miocene to present, about seventeen sub-linear to sub-parallel submarine canyons have formed along the subsiding Baiyun Sag with a water depth range of 600–1700 m, with a distinct U- or V- shaped valley characteristic imaging on the seismic section (Zhu et al., 2010). With the interplay of bottom current and turbidity current, the submarine canyons show a directional migration from southwest to northeast along the continental margin (Zhu et al., 2010). BSRs are identified mainly along the ridges between submarine canyons, and drillings show gas hydrate is deposited in silt and silt-clay sedimentary sections (Wang et al., 2011; Yang et al., 2015; Zhang et al., 2007). In 2017, the first gas hydrate production test targeting the fine-grained reservoir in the Shenhu area was conducted successfully and it is proved that the high concentrated gas hydrate in fine-grained sediment is eligible for exploitation. In this paper, our study area is mainly comprised of alternating-distributed four submarine canyons (marked as C1, C2, C3 and C4 in Fig. 1b) and five ridges (marked as R1, R2, R3, R4 and R5 in Fig. 1b) at water depth varying 1000–1300 m.

3. Data and methods

A site SC-W03-2017 (SC03) located in the ridge R3 was selected for Logging While Drilling (LWD) logging and coring for both GMGS 3 and GMGS 4 expedition (Yang et al., 2017b). The LWD data from two expeditions show a consistent result at site SC03, indicating the high quality of the LWD logs (Yang et al., 2017b). The gamma ray, resistivity and sonic logs digitalized from Yang et al. (2017b) are used in this study. Besides, two perpendicular lines intersecting site SC03 are extracted from a 3D seismic dataset. The line L1 is extracted in the inline direction (N-S) while the line L2 is extracted in the crossline direction (W-E). The field sample interval of the 3D data was set at 2 ms. The offset between the source and receivers was at approximately 370 m. These dataset are processed at 4 ms sampling rate with bin spacing of 12.5 m and 25 m in the inline and crossline directions respectively. We deal with the seismic lines as common 2D seismic profile, thus, we use terms such as CMP to describe them in this paper.

Gas hydrate saturations at site SC03 are calculated from electrical resistivity log data using the modified "quick-look" Archie equation with assumptions that gas hydrate fills in the pore space of the sediments (Collett, 1998; Wang et al., 2011). The resistivity of water-saturated sedimentary interval (R_0) is computed by fitting the baseline of the non gas hydrate-bearing sediments:

$$R_0 = 0.00135z + 1.30416. \tag{1}$$

Thus, the gas hydrate saturation (S_h) is calculated using the Archie (1942) equation:

$$S_h = 1 - \left(\frac{R_0}{R_t}\right)^{1/n}, \tag{2}$$

where R_t is the measured resistivity and n is a constant (we use $n = 2$ in this case).

In this paper, an acoustic impedance profile is obtained from the inversion of seismic data with the well logs at site SC03 as constraint using a constrained sparse spike inversion (CSSI) package (Jason, 2010). Gas hydrate saturations can be estimated from the acoustic impedance profile by introducing the water-filled porosity φ_f, which is defined as $\varphi_f = S_w \varphi$ (Lee and Collett, 2001; Lu and McMechan, 2002). Thus, the gas hydrate saturation (S_h) is estimated using the follow equations:

$$S_h = 1 - \left(\frac{R_0 \varphi_f^m}{aR_w}\right)^{\frac{1}{n}}. \tag{3}$$