Gas hydrate and associated free gas in the Dongsha Area of northern South China Sea

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A B S T R A C T

A large ongoing cold seep, named Jiulong Methane Reef, was discovered in the Dongsha Area of northern South China Sea (SCS) in 2004. To understand links among seafloor methane seepage, subsurface gas hydrate, origin of gas source and structural styles controlling the formation and accumulation of gas hydrate, high resolution multi-channel seismic data were interpreted in this region. Bottom Simulating Reflectors (BSRs), known as the base of gas hydrate stability zone, were identified and mapped. Additionally, seismic attributes, interval velocity model, and acoustic P wave impedance were obtained to better delineate the spatial distribution of gas hydrates. Hydrate-bearing sediments are characterized by weak reflection (i.e. blanking zone) above BSRs, high velocities and relatively small acoustic impedance differences, while enhanced reflection, low frequency, and low velocities beneath BSRs suggest the presence of underlying free gas beneath solid hydrate. A number of faults, mud diapirs and a possible submarine landslide were observed in seismic profiles. Both faults and mud diapirs are useful conduits, allowing methane gas to migrate upward and linking free gas zones beneath BSRs, hydrate zones and seafloor methane seepage. A submarine landslide with a length scale of ~10 km is observed in a seismic profile. The landslide may trigger dissociation of gas hydrate, accounting for the occurrence of Jiulong Methane Seepage. Seismic observations and estimated heat flow coupled with geochemical analyses suggest that gas source of methane in this region probably originates from mixture of biogenic and thermogenic methane. This study would not only help to understand gas hydrate system in the Dongsha Area, but also provide insights to geological hazards associated with the dissociation of gas hydrate.

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1. Introduction

Over the past decades, there have been considerable and increasing interests in gas hydrate worldwide owing to its important role on climate change and potential future energy resource. Gas hydrate is an ice-like crystalline substance, trapping a large amount of gas molecules within water molecule lattices (Kvenvolden, 1993). It extensively occurs on continental slopes and rises under suitable temperature and pressure condition. The zone where gas hydrates exist is called gas hydrate stability zone (GHSZ). The distribution of GHSZ is primarily governed by geothermal gradient, bottom water temperature, pressure, gas composition and pore water salinity, etc. Changes of the base of GHSZ may cause dissociation of gas hydrate and, hence, reduce continental slope stability, leading to submarine landslides (Kvenvolden, 1993; Paull et al., 2000; Mienert et al., 2001). While, in contrast, the submarine landslides may affect the formation and dissociation of gas hydrate. Therefore identifying and mapping the spatial distribution of gas hydrate are significantly important to evaluate its role on potential future energy resource, and understand geological hazards on continental margins.

The Dongsha Area is located in the northeastern continental slope of South China Sea (SCS) (Fig. 1a). Bottom Simulating Reflectors (BSRs) and blanking zones indicating the existence of gas hydrate in SCS were reported by some researchers (e.g. Song and Geng, 2000; Wu et al., 2005; McDonnell et al., 2000; Shyu et al., 2006). McDonnell et al., 2000 demonstrated that the Dongsha Area is the most promising area in the northern SCS for the occurrence of gas hydrate from tectonic and sedimentary perspectives. Additionally, a large active cold vent, named as Jiulong Methane Reef (JMR) (Fig. 1b), was discovered in 2004 during the joint Chinese–German RV SONNE Cruise 177 (Suess, 2005; Han et al., 2008),...
most likely implying that massive amounts of methane occurs in this region (Suess, 2005). Chinese—German investigation validated the probability of gas hydrate occurrence and provided useful constraints to understand methane release with geochemical methods. However, it remains unclear about the spatial distribution of gas hydrate in shallow sediments. Furthermore, underlying mechanisms responsible for the occurrence of gas hydrate, and methane venting at the seafloor are still poorly understood.

In this study, we present seismic evidence for the existence of gas hydrates and free gas beneath Jiulong Methane Reef. We applied a variety of seismic techniques to delineate the distribution of gas hydrate in more detail. We first recognized and mapped BSRs using high resolution multi-channel seismic (MCS) data and their corresponding seismic attributes. In addition, we constructed an interval velocity model and carried out acoustic P wave impedance inversion to constrain our observations. These seismic data delineate the distribution of gas hydrate and shed new lights on the links among seafloor methane seepage, subsurface gas hydrate, origin of gas source and structural styles controlling the formation and accumulation of gas hydrate in the Dongsha Area.

2. Geological setting

Tectonically, the passive continental margin of the northern SCS, which connects the SCS Basin and South China Block, is controlled by complex interactions among the Eurasian, Pacific and Indian—Australian plates (Taylor and Hayes, 1983). In the northern SCS, troughs, seamounts and scarp are well-developed, and a series of sedimentary basins (i.e. Qiongdongnan Basin, Pearl River Mouth Basin, Taixinan Basin, etc) extend along the SW—NE trending with a maximum sedimentary thickness of 10 km (Peng et al., 2004). Many studies have demonstrated that the northern SCS is a promising area for the presence of gas hydrate (e.g. Song and Geng, 2000; Wu et al., 2005, 2010; McDonnell et al., 2000; Shyu et al., 2006; Wang et al., 2011; Li et al., 2012). The study area is situated at the southwest of Taixinan Basin of the passive northern margin (Fig. 1a). The morphology is very complex and presents highly variable topography in the study area, especially in the northern part, in which scarp and canyons are well developed (Suess, 2005) (Fig. 1b and c). The sea water depth ranges from 300 m to over 2000 m. A large number of faults and mud diapirs have been observed in the Dongsha Area (e.g. Shyu et al., 1998; Yan et al., 2006). Many faults penetrate the basement of basins with large displacements and some active faults can reach the seafloor (Yan et al., 2006). These faults mainly formed under extensional setting in Late Cretaceous and Paleogene (Yan et al., 2006). Fault activity was enhanced in the second extensional stage in Late Oligocene, controlling the formation and development of the first and second order tectonic units (Yan et al., 2006). Faults and mud diapirs in the Dongsha Area provide excellent tectonic environment to the formation of gas hydrate system (Yan et al., 2006).
3. Data and methods

Multi-channel seismic data of ~1200 km (Fig. 1c) were collected by Guangzhou Marine Geological Survey (GMGS) in 2004. These data were acquired with 3000 m streamers at a depth of 5 m towed with 25 m shot spacing, 12.5 m trace spacing and a 160 cubic inches airgun array at a depth of 3 m giving full fold of 60. The sample rate is 1 ms and the record length is 6 s. The seismic processing strategy and parameters are shown in the Table 1.

Seismic methods utilized herein include seismic attribute, interval velocity model and acoustic P-impedance inversion. The calculation of complex seismic trace is a kind of transformation, essentially realized by mathematical calculation to highlight amplitude, frequency or angle information (Taner et al., 1979). The outputs from analysis of complex seismic traces are the well-known instantaneous attributes, including instantaneous amplitude, instantaneous frequency and instantaneous phase. Instantaneous amplitude, reflecting lateral changes in the reflection strength, has been extensively utilized to identify BSRS and gas hydrate layers (e.g. Taylor et al., 2000; Satyavani et al., 2005). Instantaneous frequency is directly bound up with natural frequency of target sediment layers, providing a useful tool to differentiate free gas zones from the hydrate or brine-filled sediments (Satyavani et al., 2005) by identifying low frequencies, as gas bearing sands, gas reservoirs can absorb some high frequencies (Taner et al., 1979; Taylor et al., 2000). Instantaneous phase, accounting for phase information without consideration of amplitude, is a good tool for diagnosing BSR by recognizing its typical seismic characteristics, which are reversal polarity relative to seafloor reflector and crosscutting sedimentary layers.

Stacking velocities were determined from velocity analysis and then converted into interval velocities with Dix equation. In order to build a high resolution interval velocity model we picked up stacking velocity points at a small interval of 20 CDPs and with denser vertical sampling in the shallow sediments, and then Kriging algorithm was applied to interpolate. Additionally, we applied Constrained Sparse Pake Inversion (CSSI) (Jason Geosciences Workbench 2003) to carry out relative acoustic P wave impedance inversion (i.e. relative properties of band limited P-impedance inversion). Wavelet, pseudo-wells and time gate were merged and selected to derive relative P-impedance. Pseudo-wells were built using stacking velocity by assuming constant density. CSSI assumes that seismic traces are sparsely expressed by a series of strong reflection coefficients embedding into weak reflection coefficient boundaries with Gauss’s distribution. The purpose of CSSI is to determine these weak reflection coefficient boundaries. The objective function is expressed as: OBJF = \sum |r_i| + \lambda |d_j - s_j| + \alpha^2 \sum (l_i - z_i)^2, where OBJF is the objective function; r_i is reflection coefficient; d_i is seismic data; s_i is the synthetic seismic record; \lambda is weighted coefficient; \alpha is trends of matching coefficient; p, q are L model factors (p = 1, q = 2); t_i is trends of well log. In this study, due to the absence of well logs, we estimated the trends from pseudo-wells. The parameter \lambda is responsible for the trade-off between misfit of seismic data and synthetic seismic record, and resolution. Therefore a suitable \lambda is required to get reliable P-impedance inversion results. In this study, we set \lambda = 11 after comparing the fitting of real and synthetic seismic record in a number of experiments.

4. Results and observations

4.1. Analysis of BSRS

In order to delineate the spatial distribution of gas hydrate in more detail, we first recognized BSRS in the conventional seismic profiles. BSRS are clearly identified based on their seismic properties of mimetic seafloor reflectors, crosscutting sedimentary layers, enhanced reflection and reversal polarity relative to seafloor reflector (Fig. 2). Additionally, a series of sliding faults, scars and plains (Fig. 2a and c) may imply the existing of submarine landslide in this region. The relationship between submarine landslides and the formation of gas hydrate will be discussed in the next section. A number of studies (e.g. Taylor et al., 2000; Satyavani et al., 2005) have suggested that seismic attributes can provide an excellent mean for identifying gas hydrate and underlying free gas. We extracted seismic attributes, including instantaneous amplitude, instantaneous frequency and instantaneous phase, from seismic traces to better constrain the spatial distribution of BSRS. The BSRS are characterized by enhanced amplitude from 1.2 to 2.2 s in the instantaneous amplitude profile (Fig. 3a). Weak amplitude zone (i.e. blanking zone) is observed above BSRS (Fig. 3a), likely implying that solid hydrate fills the porous space of sediments (Lee and Dillon, 2001). Similar observations in instantaneous amplitude attribute have been made in the Shenhua Area of the SCS (e.g. Li et al., 2012). A large low frequency zone is observed below BSRS extending to deep sediments in the instantaneous frequency profile (Fig. 3b), suggesting the occurrence and distribution of free gas beneath solid hydrate. In the instantaneous phase profile (Fig. 3c), the BSRS clearly cut across other seismic events and parallel the seafloor.

To further support the interpretation of BSRS, we modeled the depths of BSRS from geothermal gradient using simple conductive heat transfer model by assuming that BSRS mark the base of GHSZ. We first calculated seabed temperature from relationship between seabed temperature and sea water depth derived from CTD measurements (Wang et al., 2005), given by ln H Retrieve = –1.3361 ln T Retrieve + 2.0339, where H Retrieve is sea water depth in km and T Retrieve is the temperature of bottom sea water in °C. We performed time–depth conversion using Hamilton’s geoaoustic model (Hamiton, 1980) derived from terrigenous sediments in drill-holes in 20 areas, expressed as Vavg(t) = 1511 + 1041 \times t – 372 \times t^2, where t is the one-way travel time below seafloor in s, and Vavg(t) is the average velocity below seabed. Thus, the depth can be obtained from z(t) = Vavg(t) \times t. Some studies in nearby regions (e.g. Chi et al., 1998; Shyu et al., 2006; Schnurle et al., 2006; Schnürle et al., 2011) have suggested that this time–depth relationship is in good agreement with those from measured OBS data. Gas hydrate recovered in the expedition in the Shenhua Area of northern SCS in 2007, consists of 96.10–99.82% methane. Therefore, we determined the temperature of BSRS using P–T stability conditions for pure methane hydrate in sea water (i.e. 35% NaCl) from the CSMHYD program (Sloan, 1998). Given a specific geothermal gradient, we can model the depths of BSRS from the difference between temperature at seabed and BSR depths.

### Table 1

<table>
<thead>
<tr>
<th>Processing steps</th>
<th>Processing parameters</th>
</tr>
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<tbody>
<tr>
<td>Filter</td>
<td>8, 10, 180, 200 Hz</td>
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<tr>
<td>Amplitude compensation</td>
<td>Time compensation coefficient: 1.5</td>
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<tr>
<td>Predicted deconvolution</td>
<td>Predicted length: 16 ms; Operator length: 180; White noise coefficient: 0.1</td>
</tr>
<tr>
<td>Surface-consistent deconvolution</td>
<td>Factor length: 160 ms</td>
</tr>
<tr>
<td>Velocity analysis</td>
<td>Each velocity analysis point per 10 CDP”4</td>
</tr>
<tr>
<td>DMO stacking</td>
<td>Highest frequency: 280 Hz</td>
</tr>
<tr>
<td>Denoising after stacking</td>
<td>Window length: 1000 ms; Correlation shot: 7</td>
</tr>
<tr>
<td>Migration</td>
<td>Velocity depending on the every shot</td>
</tr>
<tr>
<td>Filtering after stacking</td>
<td>8, 12, 250, 280 Hz</td>
</tr>
</tbody>
</table>
Figure 2. (a) A seismic profile illustrating the distribution of BSRs. The location of profile is shown in Figure 1. BSRs distribute discontinuously in both upper and lower part of slope (as shown as orange line). A large canyon with a depth of ~200 m is observed in the NW of the seismic profile. Three sliding faults (marked by black lines) are presented in the low part of continental slope and deformed sedimentary layers (marked by blue box) show nearby these sliding faults. A series of scarps (?) and plains are observed. Dash line denotes interpreted slip plane of the landslide. These characteristics indicate continental slope instability in the Dongsha Area. (b) Enlarged view of the part of seismic profile illustrating the distribution of BSRs in the upper part of the slope. The BSRs (marked by light blue arrows) are characterized with sub-parallel seafloor, reversal polarity relative to seafloor, and crosscutting sedimentary layers. (c) Enlarged view of the part of seismic profile illustrating the distribution of BSRs and slip plane in the lower part of the slope. BSRs have similar characteristics to those in b. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 4 illustrates the observed and estimated BSRs using different geothermal gradient (i.e. 30, 40, 50 and 60 °C/km) for a part of a seismic profile (Fig. 2c). The estimated BSR depths using the geothermal gradient of 50 °C/km are in good accordance with the observed BSR depths. The average geothermal gradient estimated from heat-probe measurements in the offshore southwestern Taiwan, which located at east of our study area, is ~55 °C/km (Shyu et al., 2006). Considering the errors from P–T curve for gas hydrate and parameter estimations, this agreement indicates that observed BSR is reliable.

4.2. Velocity and acoustic impedance evidence of gas hydrate and free gas

Other diagnostic features, which can be utilized to indicate the occurrence of gas hydrate and free gas beneath the BSRs, include velocity variation and acoustic impedance. Recent studies have demonstrated that velocities are relatively high in hydrate-bearing sediments and would greatly be reduced due to the presence of underlying free gas (e.g. Singh et al., 1993; Hyndman et al., 2001; Pecher et al., 2001). Herein, interval velocity model was built from stacking velocities using Dix equation. Figure 5 presents an interval velocity model and its corresponding seismic profile. The high interval velocity zone above BSRs in the shallow sediments, ranging from 1600 to 2200 m/s, is interpreted as gas hydrate-bearing sediment layers. The velocity ranges are well consistent with those in other regions (e.g. Pecher et al., 1996; Korenaga et al., 1997; Mienert and Posewang, 1999). Free gas is characterized by low velocities varying from 1200 to 1500 m/s, which is also in good agreement with observations in other study areas (e.g. Korenaga et al., 1997; Tinivella and Accaino, 2000; Bünz et al., 2005). To further supplement our interpretation and delineate the spatial distribution of hydrate and associated free gas, relative acoustic impedance is derived using the CSSI. A number of studies (e.g. Zhang et al., 2011) have demonstrated the hydrate-bearing sediments are characterized by high acoustic P-impedance. However, we obtained relative impedance profiles in this study owing to lack of constraints from well log. Figure 6 illustrates a conventional seismic profile and its corresponding relative acoustic impedance and interval velocity profiles. BSRs are identified in the conventional seismic and relative acoustic impedance profiles owing to their enhanced amplitude and relatively large impedance difference. Additionally, in the relative acoustic impedance profiles, relatively low impedance differences exist above BSRs, possibly suggesting that hydrate evenly distribute in the sediments. Near-vertical faults are well developed in this area (Fig. 6b). Some of faults cut through BSRs, suggesting that faults may provide good conduits for gas migrating upward for the formation of gas hydrate in the shallow sediments. Correspondingly, the velocities are higher above BSRs compared to those beneath BSRs, placing useful constraints on the spatial distribution of gas hydrate.

In addition to clear BSRs developed in some seismic profiles, we also noticed that some blanking zones exhibit in some parts of seismic profiles (Fig. 7a), where BSRs are not observed, at the potential depth of BSRs beneath seafloor. We interpreted this amplitude blanking zone as solid gas hydrate. A number of studies (e.g. Kvenvolden and Kastner, 1990; Tinivella and Lodolo, 2000) have reported that gas hydrate exists in the area where BSRs are not observed. The lack of BSRs in the seismic profile may indicate the lack of free gas beneath solid hydrate, which could be resulted from either formation rate of gas hydrate faster than the generation of gas by hydrate recycling (Haacke et al., 2008; Lin et al., 2009) or gas source origin from the flanks of diapir (Figs. 7 and 9b), not from underlying sediments below hydrate. In
this case, interval velocity model and relative impedance profiles are powerful tools to infer the presence of gas hydrate. Some studies have suggested that both the hydrate-bearing sediments (e.g. Shipley et al., 1979; Lee and Dillon, 2001) and the homogeneity of sediments (e.g. Holbrook et al., 1996) may contribute to remarkable decreases of amplitude. However, a blanking zone, observed in the conventional seismic profile (Fig. 7a) and P-impedance profile (Fig. 7b), coupled with relatively high velocities (Fig. 7c) at the potential BSR depths indicate the presence of gas hydrate in this profile.

Figure 8 exhibits the distribution and thickness of GHSZ interpreted from the observed BSRs in conventional seismic sections and instantaneous seismic attribute sections, and interval velocity model and P-impedance profiles. The GHSZ primarily distributes on most parts of the continental slope and thickness ranges from 100 to 300 m. The distribution of GHSZ is well-correlated with the occurrence of methane seepage at the seafloor (Fig. 1b), implying a strong link between methane venting and subsurface gas hydrate.

5. Discussions

5.1. Structural controls on links among gas hydrate, free gas and methane leakage in the Dongsha Area

BSRs are observed in the conventional reflection seismic profiles, instantaneous amplitude and phase profiles. Additionally, in some seismic profiles we identified fault systems and mud diapirs, which are thought to have associated with the formation and accumulation of gas hydrate. Figure 6b shows a set of interpreted sub-vertical faults, extending from shallow sediment layers down...
to basement. The origin of the faulting might be as the result of a simple shear response to crustal extension (Hayes et al., 1995). Some of these faults cut through BSRs reaching up to the seafloor, allowing us to believe that the fault system links the free gas zones below BSRs, hydrate zone, and methane seepage at the seafloor. It has been known that faults have been thought as conduits for gas migration upward in the SCS (e.g. Yan et al., 2006; Li et al., 2012). Figure 9a schematically shows how fault systems control on the formation and distribution of gas hydrate; (c) corresponding interval velocity model, further supporting the occurrence and distribution of gas hydrate characterized by high interval velocity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 6. The distribution of gas hydrate predicated by conventional seismic profile, relative acoustic P wave impedance inversion profile and interval velocity model. The location is shown in the Figure 1c (a) conventional seismic profile showing the distribution of BSRs (represented by white arrows); (b) relative acoustic P wave impedance inversion profile illustrating the relationship between gas hydrate and fault system. Green color is small impedance differences and red color is large impedance differences. BSRs are characterized by relatively high acoustic P wave impedance differences. Complex fault system, acting as a useful pathway, is closely associated with the formation and accumulation of gas hydrate; (c) corresponding interval velocity model, further supporting the occurrence and distribution of gas hydrate characterized by high interval velocity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 7. Same as Figure 6, except for a different profile. Location is shown in the Figure 1c. (a) Conventional seismic profile. But we don’t observe BSRs in this profile. Instead, we observe enhanced amplitude indicating the occurrence of gas hydrate. A mud diapir (marked by white dash line) is observed by its weak amplitude and some pull-up events. (b) Relative acoustic P wave impedance inversion profile illustrating the relationship between gas hydrate and mud diapir. Mud diapir (circled by dash line) is another fluid flow migration conduit, allowing deeply-seated gas move upward to GHSZ to form gas hydrate. Green color is small impedance differences and red color is large impedance differences. The white arrows represent gas migration direction. Red line denotes a fault near the diapir. (c) Corresponding interval velocity model, further supporting the occurrence and distribution of gas hydrate characterized by high interval velocity. Additionally, the shape of mud diapir also can be observed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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A mud diapir is observed in the relative acoustic impedance profile, characterized by relatively small acoustic P-impedance differences and an acoustic pull-up feature within the mud diapir (Fig. 7b), suggesting that gas may migrate up along mud diapirs to form gas hydrate (e.g. Hustoft et al., 2007; Plaza-Faverola et al., 2010; Petersen et al., 2010). A large build-up with conical or volcano-like shape (i.e. mud volcano?) observed at the seafloor (Fig. 7) further indicates that the acoustic pipe is a mud diapir. The formation of mud diapirs is associated with rapid sedimentation (Milkov, 2000). An average sedimentation rate of 46 cm/ky since 1.1 Ma (Bühring et al., 2004) has been suggested from sediments recovered at ODP Site 1144, which is located at SW of our study area (Fig. 1a). A large amount of terrigenous particles and organic matter from Pearl River and/or Taiwan buried due to rapid sedimentation and converted into methane under rapid subsidence setting, providing favorable gas source for the formation of gas hydrate. Furthermore, anomalous overpressure resulted from rapid compaction (Osborne and Swarbrick, 1997) in the sediments allows underlying low density mud sediments move upward (e.g. Hustoft et al., 2009), and pierce overlying sediment layers and even seafloor to form mud volcano(?) (Fig. 7). Figure 9b is the schematic diagram illustrating how mud diapirs control the distribution of gas hydrate. The mud diapir as well as faults can provide useful conduits to methane gas in deep upward migration, linking deep-seated gas sources, hydrate zones and seafloor methane seepage. In this context, gas hydrate accumulates upward from base of GHSZ as free gas in deep sediments moves upward through fault systems and mud diapirs into GHSZ.

5.2. Slope instability, methane seepage and gas hydrate

Some studies (e.g. Bünz et al., 2003) have suggested that major submarine slide events in deep water are probably associated with the formation and dissociation of gas hydrate. Thus, understanding the relationship between submarine slide and the formation and dissociation gas hydrate would help us to explain triggering mechanism of methane venting and submarine landslide at the seafloor in the Dongsha Area. The identification of submarine slope instability mainly depends on observation of seafloor morphology and sediment deformation (Coleman and Prior, 1988). Submarine slump has been suggested to be extensively developed in this region (Yan et al., 2006). As shown in the seismic profile of Figure 2a, an area characterized by steep seafloor (~8°) and deformed sedimentary layers likely implies the existence of submarine landslide in this region. Further, a series of sliding faults, scarps and plains at the steep seafloor further support the occurrence of landslide. An unconformity following the base of the high amplitude zone (as shown by the dash line in Fig. 2a) is interpreted as a sliding plane, implying the length scale of the landslide is approximately 10 km. These seafloor morphology and sediment deformation allow us to infer that the slope is not stable, which may be caused by the existing of extremely large overpressure, as shown by existence of the mud volcanoes(?), massive methane venting at the seafloor (Suess, 2005), and fault movement (Fig. 6b). Alternatively, the deformed sedimentary layers may indicate the occurrence of sediment waves caused by sliding faults. Gong et al. (2012) observed a large area of sediment waves in the south of our study area. However, it’s much more plausible to interpret it as submarine landslide in such steep slope gradient (~8°) with complex seafloor morphology.

Submarine landslide would alter the morphology and elevation of seafloor analogous to the effects of fault movement in seafloor. Figure 10 illustrates how the base of GHSZ responds to variation of seafloor elevation. The distribution of GHZS is controlled by phase diagram of gas hydrate, temperature at the seafloor and geothermal
gradient (Fig. 10a). Landslides would cause the dissociation of gas hydrate (e.g. Bünz et al., 2003). As shown in Figure 10b, a new base of GHSZ will form correspondingly to balance the variations of pressure and temperature and new gas hydrate will form from parts of free gas produced by hydrate recycling. In contrast, the dissociation of gas hydrate due to temperature rising or dropping at the seafloor, or sea level variation, is thought to have contributed to slides at deep water (e.g. Maslin et al., 1998). When the temperature at seafloor increases (shown from point A to point B in Fig. 10b), the base of GHSZ (marked by BSR in Fig. 10b) would shift upward to a new base of GHSZ (marked by dash green line in Fig. 10b), inducing dissociation of gas hydrate.

5.3. Origin of gas source

An understanding of gas source of hydrate is of significant for evaluating their distribution and potential of hydrate and associated free gas. Gas hydrate can originate from either thermogenic or biogenic gas, or combination of both. A number of investigations show that gas hydrate worldwide primarily derives from mixed thermogenic and biogenic methane, e.g. in offshore western Canada (Riedel and Rohr, 2012); Kongsfjorden shelf (Knies et al., 2004); offshore NW-Svalbard (Rajan et al., 2012). Generally, the generation of thermogenic methane requires a minimum onset temperature of 120°C (e.g. Tissot and Welte, 1984). As we discussed previously, the estimated BSR depths are in good agreement with the observed BSR depths, given a thermal gradient of 50°C/km. Thus, the sediments at depths below 2.4 km are capable of producing thermogenic methane. The sedimentary thickness in this region ranges from 4 to 5 km (McDonnell et al., 2000). Therefore the gas hydrate in this region may probably be fed by deep thermogenic methane dominantly. The seismic observations presented herein also support a deep-seated gas source, as evidenced by low frequency zones (Fig. 3b) and the occurrence of fault system and mud diapirs, which can link the hydrate zone and the deep-seated gas source. The similar links among deep-seated hydrocarbon sources, shallow gas hydrates and seabed seepages has been reported in the Svalbard shelf and slope area of Norway (e.g. Rajan et al., 2012). However, we cannot rule out that gas hydrate may have some contributions from biogenic gas in the shallow sediments and free gas produced by recycling of gas hydrate due to submarine landslide. Depleted δ13C ranging from −52.3% to −32.6% suggested that leaking methane originated from biogenic methane (Han et al., 2008). Additionally, the carbon isotopic results at Sites 1144 and 1146 ODP Leg 184 (Fig. 2a) (Wang et al., 2000) illustrated that the hydrate in the Dongsha Area is thermogenic gas or mixed gas. Therefore we concluded that the gas hydrate in this region is derived from mixture of biogenic methane in the shallow sediments and thermogenic methane in deep-seated sediments.

6. Conclusions

BSRs are extensively developed in the seismic sections. Moreover, weak reflection (i.e. blanking zone), high velocity, relatively small acoustic P-impedance differences exist above BSRs, suggesting the presence of gas hydrate in the Dongsha Area, while low frequency, low velocity and enhanced reflection indicating the existence of free gas below BSRs. These seismic indicators, together with recent discovery of massive hydrate seepage, strongly suggests favorable conditions for the formation of gas hydrate in the Dongsha Area. Fault systems and mud diapirs play a significant role on linking deeply-seated free gas zone, gas hydrate in the shallow sediments and methane seepage at the seafloor. Fault system and mud diapir provide useful pathways for gas migration upward to GHSZ to form gas hydrate in the shallow sediments, even reach to seafloor, causing methane venting in this region. Alternatively, the dissociation of gas hydrate associated with seafloor variation resulted from slope instability would also induce methane seepage. The gas source of methane probably originates from mixture of biogenic and thermogenic methane combined estimated average heat flow, seismic and previous geochemical observations together.

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