BSRs, estimated heat flow, hydrate-related gas volume and their implications for methane seepage and gas hydrate in the Dongsha region, northern South China Sea

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Abstract

To investigate the relationship among methane seepage, subsurface gas hydrate, and heat flow and estimate hydrate-related gas amount in the Dongsha region, northeastern South China Sea, in this study we first identified Bottom Simulating Reflector (BSR) using multi-channel seismic data collected in 2004. Subsequently, the thickness of gas hydrate stability zones (GHSZ) was calculated from the observed BSR using time-depth conversion, ranging from 60 to 300 m in seawater depths of 600-1200 m. Additionally, a seismic feature of double BSRs is locally observed in this region, which is possibly caused by either the presence of mixed gas source (thermogenic and biogenic) or migration of a pre-existing base of GHSZ. Geothermal gradient, heat flow and hydrate-related gas volume are calculated based on the thickness of GHSZ. The estimated geothermal gradient and heat flow varies from 20 to 100 °C/km with an average of 48 °C/km, and from 20 to 120 mW/m² with an average of 54 mW/m², respectively. Both estimated geothermal gradient and heat flow are generally consistent with those from measurements. High geothermal gradient (up to 60 °C/km) and heat flow anomaly (up to 80 mW/m²) are present in one methane seepage site, where BSR is clear and reliable. High heat flow could result in thin GHSZ in the continental slope. In this case, gas hydrate could form in the shallow sediments, making dissolved gas from hydrate and/or free deep-seated gas easy to migrate upwards to seafloor through faults, and thus resulting in the occurrence of methane venting. The hydrate-related gas volume is estimated as $\sim 6 \times 10^{11}$ m³ over an area of ~ 400 km² with possible occurrence of BSR. This finding would shed lights on understanding potential amount of subsurface methane in

the Dongsha region and place useful constraints for modeling GHSZ from measured heat flow data, especially in regions where no BSRs are present.

Keywords: Dongsha; South China Sea; Methane seepage; Gas hydrate stability zone; Double BSRs; Geothermal gradient; Heat flow; Gas volume;

1. Introduction

Dongsha region is located in the continental margin of northeastern South China Sea (SCS) (Fig. 1a). Over the past decade, an increasing interest on the detection of gas hydrate in the Dongsha region has been triggered by a discovery of active methane seepages (or venting) at the seafloor (Suess et al., 2005). A cold seafloor methane seepage, Jiulong methane seepage (JMS), was discovered in this region in 2004 during the Chinese-German joint expedition (Suess, 2005; Han et al., 2008). Large seep carbonate, carbonate nodules and crust, biogenic shells, which infer the cold seep ecosystem, were observed (Chen et al., 2006; Chen et al., 2005; Han et al., 2008). Additionally, high methane concentration in bottom water in the JMS region has been inferred from water column samples, indicating that JMS is dramatically active (Yin et al., 2008). A number of studies have suggested that the occurrence of this methane seepage is related to subsurface gas hydrate (Li et al., 2013; Zhang et al., 2014a; Sha et al., 2015). Previous studies demonstrated that the tectonic and sedimentary conditions in the Dongsha region are beneficial for the formation and accumulation of gas hydrate (Song et al., 2000; McDonnell et al., 2000; Wu et al., 2004; Yan et al., 2006; Wang et al., 2006; Lin et al., 2009; Schnürle et al., 2011; Li et al., 2012a; Li et al., 2013). For instance,

McDonnell et al. (2000) indicated that marine sediments in the Dongsha region located in passive continental margin have appropriate-thickness, methane-generating potential to host gas hydrate. Wu et al. (2004) suggested that debris flow and turbidity sediments are favorable for gas hydrate accumulation in an adjacent region. Yan et al. (2006) and Lin et al. (2009) analyzed geological features controlling the formation and distribution of gas hydrate. Furthermore, Li et al. (2013) presented seismic evidence for the existences of hydrate and free gas beneath JMS and demonstrated that the seafloor seepages in this region are a result of upward migrating free gas from dissolved hydrate and/or deep-seated gas source through mud diapirs and fault systems. Gas hydrate samples were recovered in the Dongsha region in a recent expedition (GMGS-2 expedition) conducted by Guangzhou Marine Geological Survey (GMGS) in the June-September 2013 (Zhang et al., 2014a, 2014b; Sha et al., 2015; Zhang et al., 2015). Totally 13 exploration sites were drilled at water depths of 664-1420 m. Gas hydrate samples were obtained at 5 sites and well log data at 8 sites inferred the existence of gas hydrate (Zhang et al., 2014a; Sha et al., 2015). Single-layer or double-layer gas hydrate samples are distributed in silty clay with coarse grain sizes with geometries of massive blocks, thin layers, veins, nodular or disperse particles (Zhang et al., 2014a; Sha et al., 2015). This expedition combined with other seismic and geochemical evidences confirmed the existence of gas hydrate in the Dongsha region. In this study, we used multi-channel seismic data collected in 2004 to further explore relationship among methane seepage, subsurface gas hydrate, and heat flow, and investigate hydrate-related gas volume in the Dongsha region, where multi-channel seismic data coverage is available.

The seismic survey region situates in the Tainan rift basin, northeastern South China Sea. A series of normal faults with a trend of northeast-east (NEE) have developed in this region and some of the faults were active during Pliocene and Quaternary (Yan et al., 2006; Wu et al., 2004). The seafloor morphology is characterized by complex, highly variable topography, and a large number of canyons, gullies and bathymetric ridges with NNW-SSE trend are well developed (Liu et al., 1998, 2004; Suess, 2005). The sea water depth ranges from 300 m to over 2000 m. The multi-channel seismic data used in this study have been previously reported in the paper of Li et al. (2013). Gas hydrate and free gas hydrate were inferred through identifying BSR in these seismic dataset combined with seismic attributes (Li et al., 2013). In this study, we further described various geological features associated with BSR. Additionally, the geothermal gradient and heat flow maps are constructed from the observed BSR. The relationship among methane venting, subsurface hydrate, and heat flow is investigated, which would shed lights on the detection of hydrate in regions where no BSR is observed or BSR is discontinuous. Additionally, we analyzed the causes of double BSRs, which are locally observed in seismic profiles. Hydrate-related gas volume is estimated, which would have implications for future studies on potential amount of gas releasing to atmosphere and their environmental effects.

2. Data and data processing

Approximate 1200 km multi-channel seismic (MCS) data (Fig. 1b) were acquired in the Dongsha region by Guangzhou Marine Geological Survey (GMGS) in 2004. These data were collected 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 data processing flow includes common depth point (CDP) sorting, pre-filtering, spherical divergence amplitude compensation, predictive and surface-consistent deconvolution, velocity analysis, Dip-moveout correction (DMO) stack, and migration. More details regarding to the seismic processing strategy and parameters are given by Li et al. (2013).

3. Methods

A bottom simulating reflector (BSR) is considered as the base of gas hydrate stability zone (GHSZ) and its formation is due to high P-wave velocity gas hydrate overlying free gas with low P-wave velocity (e.g. Singh et al., 1993; Hyndman et al., 2001; Pecher et al., 2001). In this study, we identified BSRs in seismic profiles, which are used to calculate the thickness of GHSZ using time-depth conversion. Furthermore, heat flow in the study region was estimated from obtained GHSZ map. The methodology used in this study was previously applied in the Shenhu region, northern South China Sea (Li et al., 2012b).

A conductive thermal model is assumed using following expression.

$$Q = K \frac{(T_{bsr} - T_{sf})}{Z_{bsr}}, \quad (1)$$

in which Q represents heat flow, T_{bsr} indicates temperature at the BSR depths, T_{sf} is the temperature at the water bottom; K is thermal conductivity; Z_{bsr} is the thickness of gas hydrate stability zone. The T_{bsr} is calculated from pressure-temperature (P-T) stability conditions for pure methane hydrate in seawater (i.e. 3.5% NaCl) from the CSMHYD

program (Sloan, 1998; Fig. 6) and T_{sf} is estimated from an empirical relationship between water bottom temperature and water depth (Fig. 2b), which is expressed by

$$\ln H_{sf} = -1.3361 \ln T_{sf} + 2.0339 \quad (2)$$

where H_{sf} is sea water depth in km and T_{sf} is the temperature in water bottom in °C. Additionally, thermal conductivity is calculated from following empirical equation (Davis, 1990; Fig. 2c).

$$K = 1.07 + 5.86 \times 10^{-4} \times Z_{bsr} - 3.24 \times 10^{-7} \times Z_{bsr}^2 \quad (3)$$

The relationship between thermal conductivity and BSR at mbsf (meters below seafloor) depths is generally consistent with that obtained from ODP sites 1148 and 1146 of SCS (Wang et al., 2000), which is to the west of our study area (Fig. 1a).

The time-depth conversion is conducted using Hamilton's geo-acoustic model (Hamilton, 1980; Fig. 2a), expressed as $V_{avg}(t) = 1511 + 1041 \times t - 372 \times t^2$, where t is the one-way travel time below seafloor in seconds (s), and $V_{avg}(t)$ is the average velocity below seabed. Time domain could be converted into depth domain using following expression $Z(t) = V_{avg}(t) \times t$.

Finally, we use Monte-Carlo simulation method to calculate gas volume bearing in hydrate in the region with seismic data coverage. The details and results about this calculation will be demonstrated in the next section.

4. Results and Discussions

4.1. BSRs and the thickness of gas hydrate stability zone

In seismic profiles BSR is characterized by high amplitude, polarity reversal relative to seafloor reflector, paralleling or sub-paralleling to the seafloor, and obliquely cutting across sediment layers. Here three seismic profiles, two of which approximately cross

methane seepage (venting) sites, are presented (Fig. 3, 4). BSR is distributed in the continental slope with two-way travel time (TWT) ranging from 1.2 s to 2.4 s (Fig. 3, 4). Normal faults are well developed in this region. As shown in Fig. 3, a number of high-angle normal faults are observed beneath the methane seepage sites. Some of these fault cut through BSR and even extend down to the basement and up to the seafloor (Fig. 3c). Additionally, a series of slump blocks are separated by a number of listric normal faults (Fig. 4a). BSR occurs in the slump blocks. These faults cutting through BSR could result in discontinuous distribution of BSR and could act as useful gas migration pathways, linking seafloor methane venting, subsurface gas hydrate, and possible deep-seated gas source (Fig. 3, 4). In the area where BSR is developed, we can observe some canyons, gullies, and possible paleo-channels. BSR occurs beneath a current canyon and gully (Fig. 4b), while possible paleo-channels are present beneath the BSR (Fig. 3d, 4b, 4c). Current canyons, gullies or paleo-channels could provide organic-rich material, which benefits for the formation and accumulation of gas hydrate. Additionally, some bright spots (high amplitude events) are present nearby the BSR, channels and possible paleo-channels (Fig. 3b), indicating the existence of rich gas in the Dongsha region.

The distribution of BSR is mapped in each survey line. Fig. 5a shows the distribution map of BSR in the two-way travel times (TWT) (seconds). The BSR mainly distributes in the continental slope in two-way travel times from 0.8 to 2.4 s with water depths of 800-1400 m. Two areas with possible BSR are identified in the study region. Area 1 defines the region where BSR is reliable with the presence of clear typical seismic features as discussed above. In the Area 2 the interpreted BSR is paralleling to the sediment layers, making them difficult to distinguish with sediment seismic events (Fig.

3a). We defined it as an area with possible occurrence of BSR. GHSZ thickness map is obtained from depth difference between BSR and seafloor and interpolated to the whole study region (Fig. 5b). Generally, within the regions where BSR occurs (outlined by dashed blue lines in Fig. 5b), the thickness of GHSZ varies from 60 to 300 m with an average of 200 m and decreases with reducing water bottom (Fig. 5b).

4.2 Possible double BSRs and their causes

An interesting seismic feature, double BSRs, is locally observed in a seismic profile (Fig. 4c). The upper BSR (marked as BSR1) is traced as a strong reflector and appears to connect with the BSR at the upper continental slope. Locally, another seismic event is interpreted to be a second BSR (marked as BSR2), identified about 1 s (~100 m) below the BSR1. BSR1 is characterized by strong negative amplitude throughout its lateral extent and paralleling to the seafloor reflector (Fig. 4c, 6c), while BSR2 is characterized by weak negative amplitude, extending over a distance of 3 km (Fig. 4c, 6c). Both BSR1 and BSR2 cut across the sediment layers (Fig. 4c). An un-interpreted high-resolution seismic profile is shown in supplementary material in order to display the seismic features of BSR1 and BSR2 more clearly (Fig. S1). Below the BSR1, a package of high amplitude events is present, likely indicating the existence of free gas. Weak amplitude (or blanking zone) is observed above the BSR2 within a possible paleo-channel. In order to further understand the occurrence of double BSRs and which one could represent the current base of GHSZ, we modeled BSR depths using present temperature and pressure conditions at the seafloor and in the sediment by assuming different geothermal gradients

and hydrate phase equilibrium curves (Sloan, 1990). The predicted BSR using 50 °C/km geothermal gradient at 100% methane with seawater approximation (3.5% NaCl) fits the observed BSR1, while the observed BSR2 approximately matches the predicted BSR using 40 °C/km geothermal gradients. The average geothermal gradient in the Dongsha continental slope region is inferred to be ~48 °C/km from the interpolated geothermal gradient map, which is constructed with previous measurements (Fig. 7) (Xu et al., 2006; Shyu et al., 2006; Liao et al., 2014). The upper BSR (i.e. BSR1) therefore likely indicate the current base of GHSZ.

Double BSRs have been observed in other regions worldwide, such as Antarctica (Geletti and Busetti, 2010), Naikai (Foucher et al., 2002), Black Sea (Popescu, 2006). Several causes have been suggested by a number of studies to explain the double BSRs (e.g. Geletti and Busetti, 2010; Foucher et al., 2000; Wu et al., 2005). The double BSRs could indicate the variation of GHSZ base caused by seafloor instability and sea water level changes (e.g. Foucher et al., 2000). As shown in hydrate phase equilibrium diagrams (Fig. 6e, 6f), uplift of seafloor (Point A to Point B), or with an equivalent effect, sea bottom warming (Point B to Point F) could induce the migration of BSR from BSR2 to BSR1. In this case, the lower BSR (i.e. BSR2) therefore could be interpreted to be a paleo-BSR. Given a choice of 50 °C/km geothermal gradient, the formation of this observed double BSRs feature is likely a consequence of BSR migration in response to a ~4 °C sea bottom warming or an event of rapid uplift of the seafloor by ~100 m (Fig. 6e, 6f). It is noteworthy that changes of geothermal gradient would correspondingly alter the sea bottom warming or the seafloor rapid uplift values.

Wu et al. (2005) observed double BSRs for the first time in the northern South China Sea and they suggested that the double BSRs could indicate the existence of thermogenic gas source. In this case, BSR2 may alternatively indicate a deeper base of GHSZ, which is caused by the presence of thermogenic gas source (molecules of heavier hydrocarbon gases than methane) (Geletti and Buseti, 2010). Here in order to investigate how the mixture of gases could generate the double BSRs, we model the deeper base of GHSZ using hydrate phase equilibrium curves (Fig. 6d) with different gas compositions. BSR2 fits the predicted BSR using hydrate phase equilibrium curves with 92% methane, 6% ethane, and 2% propane in seawater approximation. These percentages of gas compositions indicate the possibilities of thermogenic gas existence and are not necessary to reflect current amounts of different gas compositions in this region since the predicted BSR using these gas compositions with different percentages may also match the depth of BSR2. A microbial origin is suggested at the shallow depths (0~100 mbsf) at five sites of the recent GMGS-2 expedition exploration drillings with the presence of high molecular ratios of methane to ethane ratios (C_1/C_2) (Zhang et al., 2015). One drilling site (GMSG2-08) locates near the area with the double BSRs. However, the well on this site didn't reach to the depth of BSR2 (~300 mbsf). Furthermore, a sharp decrease for C_1/C_2 is observed at 202 mbsf at one site (GMSG2-16), suggesting a possible external source of fluid at this depth (Zhang et al., 2015). The existence of thermogenic gas source is suggested by Li et al. (2013) with observations of thick sediments and deep structural features in the regions with deep sea water, such as deep faults and mud diapirs, which could act as gas migration pathways to connect deep-seated gas source with GHSZ. Therefore, local existence of thermogenic gas in this region cannot be ruled out. The

carbon isotopic results at Ocean drilling program (ODP) sites 1144 and 1146 indicated that source of hydrate could be from mixture of thermogenic and biogenic gas (Wang et al., 2000). Additionally, mixture of deep thermogenic gas and shallow biogenic gas are indicated in the Shenhu region of northern South China Sea (Yu et al., 2014; Wu et al., 2011; Liu et al., 2012; Wang et al., 2014). Given these facts, the double BSRs could also be explained by the local existence of thermogenic gas at depth.

4.3 Geothermal gradient and heat flow estimated from BSRs and their implications for gas hydrate and methane venting

As shown in Fig. 5a, BSR is not distributed in the whole study area. In this study, we first calculated geothermal gradient and heat flow in the region with the occurrence of possible BSR and then used Kriging method to interpolate and extrapolate with a grid spacing of 2000 m for obtaining the distribution of geothermal gradient and heat flow in the whole study region (Fig. 7). Similar calculation is also conducted by other investigators in other regions in the northern South China Sea (Wang et al., 2005; Li et al., 2011; Li et al., 2012b). A number of measurements for heat flow and geothermal gradient have been carried out in an adjacent region by previous investigations (Fig. 7, Table 1; Xu et al., 2006; Shyu et al., 2006; Liao et al., 2014). Two measurement points situate in the northern part of our study area (Fig. 7a, 7b). Fig. 8 shows histogram distribution of estimated and measured geothermal gradient and heat flow within the grids. Generally, estimated geothermal gradient and heat flow distribution are compatible with those from measurements (Fig. 7, 8). The estimated geothermal gradient values range from 20 to 100 °C/km with an average of ~48 °C/km, and estimated heat flow values varying from 20 to 120 mW/m² with an average of ~54 mW/m² (Fig. 7 and Fig. 8). The uncertainty of

geothermal gradient calculation is difficult to quantify and are mainly due to the time-depth conversion and phase equilibrium curves. The errors from these contributions could accumulate, yielding a total error on the calculation of geothermal gradient. The time-depth conversion would generate 11% error in temperature gradient from measuring two-way-travel time in seconds (TWTs) and velocity-depth relationship, while the temperature calculation at BSR depth using hydrate phase equilibrium curve could result in approximately 7% in the geothermal gradient (Li et al., 2012b). Thus the total uncertainty in the geothermal gradient is 18%. More details regarding to the uncertainty estimations are given by Li et al. (2012b).

Fig. 7 shows the lateral distribution of estimated and observed geothermal gradient and heat flow in a regional scale and our study area. Generally, heat flow and geothermal gradient values increase in the seaward direction. Similar observations are made by other investigators in the northern South China Sea (Yuan et al., 2009; Liao et al., 2014). In a regional scale (Fig. 7a, 7b), high geothermal gradient distributes in the continental slope, while continental shelf is characterized by low geothermal gradient. When only focusing on our study area (Figure 7c, 7d, 7e and 7f), generally, the variation trend of observed and estimated geothermal gradient and heat flow are similar. It's worth noting that there are no published direct geothermal gradient and heat flow measurement points in the seismic survey region and the observed geothermal gradient and heat flow maps can only provide a broad picture for geothermal gradient and heat flow distribution. Therefore the estimated geothermal gradient and heat flow maps from the observed BSR could provide detailed constraints in our study region.

Three methane seepage sites are recognized in our study area (Suess, 2005; Han et al., 2008). A clear BSR is present beneath methane seepage site 3, while no BSR is observed or the observed BSR is located at the edge of the BSR distribution area in the methane seepage sites 1 and 2. These two sites could have large uncertainties for geothermal gradient and heat flow estimations. Therefore, we would just focus on methane seepage site 3 in an attempt to investigate the relationship among methane seepage, gas hydrate, and heat flow. As shown in the estimated geothermal gradient (or heat flow) map, the methane seepage site 3, which has more reliable BSR identification, is characterized by anomalously high geothermal gradient (or heat flow). Macelloni et al. (2015) discovered a close correlation between high heat flow and methane seepage, and they suggested that the high heat flow is closely associated with inferred fluid flow and faulting in the methane seepage regions. As shown in Fig. 3b, beneath the methane seepage site 3 a high-angle normal fault is observed, extending from seafloor down to BSR, and even to the basement, which could act as a migration channel of fluid flow and link the deep-seated gas sources, subsurface gas hydrate and seafloor methane venting in this region. Additionally, a basement high is also observed beneath the methane seepage site 3 (Fig. 3b). This basement high combined with faulting could induce high heat flow (Liao et al., 2014), and hence result in thin GHSZ in this region, which can be reflected by the distribution of BSR in the seismic profile as shown in Fig. 3 and Fig. 4. This also can be observed in the BSR modeling using hydrate phase equilibrium curves and different geothermal gradients. As geothermal gradient increases the thickness of GHSZ decreases (Fig. 6a). In this case, in the regions with particular high heat flow, gas hydrate could form in the shallow sediments near seafloor, making dissolving gas from hydrate

easy to move upward seafloor through faults and thus inducing the formation of methane venting, as we observed in this region. A more detailed heat flow survey and high-resolution seismic and AUV (Autonomous underwater vehicle) data (e.g. side-scan sonar, sub-bottom profiler; multi-beam bathymetry) are needed to better understand the relationship among tectonic activities, heat flow, hydrate and seafloor methane venting, such as how the basement high and faulting result in high heat flow and how hydrate responses to these tectonic activities.

4.4 Estimated Gas hydrate volume and implication for methane venting

Here we use Monte Carlo methods to estimate gas volume bound in hydrate in the study area. Monte Carlo simulation is carried out using following equation: $V = A \times \Delta z \times \phi \times H \times E \times R$ (Gornitz and Fung, 1994), where A is the area with BSR occurrence; Δz is the thickness of GHSZ; ϕ is effective sediment porosity; H is hydrate-filled saturation; E is gas expansion factor for methane; R is degree of hydrate mineralization. The BSR occurrence area (A), where BSR occurs (Fig. 6a), is approximately 400 km². Given the uncertainty of BSR identification, we allow the area (A) to vary between 200 and 600 km². The thickness of GHSZ varies from 60 to 300 m with an average of 200 m determined from seismic data. Saturation is measured as 45%-100% from well log data from GMGS-2 expedition (Zhang et al., 2014a). The porosity calculated from borehole measurements yielded values over 45% (Zhang et al., 2014a). The methane expansion factor we used here is 157-163. GMGS-2 expedition drilling data indicate that the gas hydrate exists at layers in a thickness of 10-50 m above the observed BSR depth (Zhang et al., 2014a). Degree of hydrate mineralization is therefore approximately at ~15% given an average GHSZ thickness of 200 m. The input values of various parameters are

selected based on above observations (Table 2). We used Monte Carlo simulation, which randomly sample the stochastic input parameters, to provide a broad picture of output hydrate-related gas volume distribution and possibilities. Model was computed for 100000 iterations. The most likely gas volume bound in hydrate is approximately $6 \times 10^{11} \text{ m}^3$ with a range of $2 \times 10^{11} - 16 \times 10^{11} \text{ m}^3$ given above parameters (Fig. 9). These large amounts of gas hydrate could release into seawater and atmosphere over a geological scale. However, how hydrate releases and how much of them would release or have released in this region require further geochemical and geophysical studies, which is beyond this study.

5. Conclusions

BSR is distributed in the continental slope in the Dongsha region, northeastern South China Sea, accompanied with a variety of geological features, such as normal faults and listric normal faults, canyons and gullies, paleo-channels, and slump blocks. Faults could act as good migration pathways for deep gas source to migrate upwards to the GHSZ, and even up to the seafloor. Current canyons, gullies and paleo-channels could provide organic-rich material, which benefits for the formation of gas hydrate. Possible double BSRs are locally observed in the lower continental slope and their formation is attributed to either the existence of deep thermogenic gas, or the variation of GHSZ base owing to bottom water temperature warming or rapid tectonic uplift. Additionally, geothermal gradient and heat flow are estimated from the thickness of GHSZ. The lateral distribution of estimated geothermal gradient and heat flow from GHSZ are generally consistent with those from measurements. An anomalously high geothermal gradient (high heat flow), likely resulted from faulting and a basement high,

could result in thin GSHZ. Gas hydrate could therefore form in the shallow sediments, making free gas from dissolved hydrate/deep-seated gas source easy to move upwards to the seafloor. This process would result in the formation of methane venting, which is observed in the region with high heat flow values. Hydrate-related gas volume is estimated as most likely $6 \times 10^{11} \text{ m}^3$ using Monte Carlo simulation method over an area of $\sim 400 \text{ km}^2$ with possible occurrence of BSR.

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Figure captions

Fig. 1 (a) Topographic map of northeastern South China Sea. Location is shown as a solid black line box in the embedded map. The big blue box represents the location for Fig. 7a. The black box represents the study area, where multi-channel seismic lines in Fig. 1b were collected. Red line with triangles indicate Manila subduction belt. SCS, South China Sea; CS, Continental Shelf; FC, Formosa Canyon. Black points represent Ocean Drilling Program (ODP) drilling sites. (b) Bathymetric map of study area and multi-channel seismic survey. Location is shown in Fig. 1a. The blue lines indicate the location of multi-channel seismic lines in Fig. 3 and Fig. 4. Three methane venting sites are shown as blue triangles. The area outlined by blue dash lines is GMGS-2 expedition drilling region.

Fig. 2 Models for the calculation of heat flow. (a) Time-depth conversion model; (b) Relationship between bottom water depth and seafloor temperature; (c) Relationship between thermal conductivity and depth (mbsf). The solid line is from Davis et al. (1990). The open red triangles and star points denote the measurements of thermal conductivity from ODP sites 1148 and 1146 of SCS, respectively.

Fig. 3 (a) A seismic profile across methane venting Site 2 with the identification of BSRs. The location of profile is shown in Fig. 1b. The yellow arrows direct towards the distribution of BSRs. The bold dashed line represents the interpreted Mesozoic basement. The blue triangle indicates the locations of methane venting Site 2. (b) Same as Fig. 3a, except across methane venting Site 1 and Site 3. (c) Enlarged seismic session. The black solid lines are interpreted faults and the dashed lines represent possible faults. (d). Same as Fig. 3c, except for different session.

Fig. 4 (a) A seismic profile illustrating the distribution of BSRs and double BSRs. (b) Enlarged seismic session illustrating the distribution of BSRs in the upper part of the slope. Bright spot, canyon, fault and gully are also observed in the profile. (c) Enlarged seismic session illustrating the occurrence of double BSRs in the lower part of the slope. The yellow arrows direct towards the upper BSR (BSR1), which likely indicate current base of gas hydrate stability zone, while the white arrows direct towards the lower BSR (BSR2).

Fig. 5 (a) Distribution map of BSRs in the two-way travel times (s). The red triangles indicate the methane venting sites. (b) The interpolated thickness distribution of GHSZ calculated from the observed BSRs using time-depth conversion.

Fig. 6 The double BSRs and hydrate equilibrium curves for interpretation of BSRs. (a) Enlarged view of seismic session for the occurrence of double BSRs and the predicted and observed base of the GHSZ (i.e. BSR) using different geothermal gradients (i.e. 30, 40, 50, 60 °C/km). Location of profile is shown in Fig. 4c. (b) Enlarge view of seafloor seismic event. (c) Enlarged view of double BSRs. (d) Phase equilibrium curves with different gas compositions. (e)-(f) Phase diagrams of GHSZ illustrating the base of gas

hydrate (i.e. BSRs) responds to changes of seafloor morphology and sea water warming. When the seafloor uplifts (from point A to point B) or the temperature of bottom water increases (from point B to point F), the base of GHSZ would shift upward to a new base of GHSZ (marked by BSR1) (from point E to point D or from point C to point D).

Fig. 7 Estimated and observed geothermal gradient and heat flow. (a) Interpolated geothermal gradient map in a regional scale from previous measurement points (Xu et al., 2006; Shyu et al., 2006; Liao et al., 2014). Blue, green and black triangles are the measurement points from Xu et al. (2006), Shyu et al. (2006), and Liao et al. (2015), respectively. The blue box represents our study area and the small black boxes indicate the locations of methane seepage sites. (b) Same as Fig. 7a, except for heat flow. (c) Enlarge map of interpolated measured geothermal gradient in the study region, where multi-channel seismic data were collected. (d) Same as Fig. 7c, except for estimated geothermal gradient. (e) Enlarge map of interpolated measured heat flow in the study region. (d) Same as Fig. 7f, except for estimated heat flow.

Fig. 8 (a) The histogram of thickness of GHSZ. (b) The histogram of geothermal gradient values. Blue color is for measure geothermal gradients and black color is for estimated geothermal gradients (c) Same as Fig. 8b, except for heat flow values.

Fig. 9 The probability histogram for total hydrate-related gas volume estimation

Table 1: Measured geothermal gradient and heat flow

Shyu et al. (2006)			
Longitude	Latitude	Geothermal Gradient (°C/km)	Heat flow (mW/m ²)
119.6525	22.3168	48	47
119.4863	22.1735	65	57
119.8072	22.162	39	34
120.1107	21.9512	42	36
120.0623	21.9507	69	66
119.5001	21.7899	69	67
119.6704	21.7487	74	70
119.9684	21.8466	67	69
120.0873	21.8864	58	61
120.3932	21.9922	51	50
119.8998	21.64	56	62
119.3389	21.7304	90	85
119.5621	21.7189	59	59
119.9119	21.7102	63	65
119.8104	22.0907	66	56
119.8192	21.7946	53	51
120.0601	21.6924	49	55
119.8813	22.2533	38	36
120.5535	21.5184	38	42
120.1637	21.4544	42	50
120.0502	21.4342	73	87
119.7181	21.3808	70	75
Xu et al.(2006)			
119.065	21.531	78	81
Liao et al. (2014)			
118.7346	22.4287	24.9	39.28
119.2853	22.5074	41.9	76.98
119.3469	22.5332	37.4	68.15
119.2953	22.55	34.8	64.28
119.3131	22.4981	37.6	68.61
119.3112	22.5241	38	64.64
119.3112	22.6981	33.7	64.61
118.6585	22.2166	24.7	43.86
119	22.2434	40.3	73.87

Table 2: The inputs setting for Monte Carlo simulation to estimate hydrate-bound gas in-place in the study area

Input parameters	Distribution	Mean	standard deviation	Min	Max
Area (A) for occurrence of GH	normal	400 km ²	60	200 km ²	600 km ²
The thickness of GHSZ	normal	200 m	25	125 m	275 m
Effective sediment porosity	normal	0.6	0.08	0.35	0.85
Hydrate-filled saturation (H)	normal	0.6	0.08	0.35	0.85
Gas expansion factor methane	normal	160	1	157	163
degree of hydrate mineralization	normal	15%	3%	5%	25%

Figures

Fig. 1

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