

## Geothermal investigation of the thickness of gas hydrate stability zone in the north continental margin of the South China Sea

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### Abstract

The exploration of unconventional and/or new energy resources has become the focus of energy research worldwide, given the shortage of fossil fuels. As a potential energy resource, gas hydrate exists only in the environment of high pressure and low temperature, mainly distributing in the sediments of the seafloor in the continental margins and the permafrost zones in land. The accurate determination of the thickness of gas hydrate stability zone is essential yet challenging in the assessment of the exploitation potential. The majority of previous studies obtain this thickness by detecting the bottom simulating reflectors (BSRs) layer on the seismic profiles. The phase equilibrium between gas hydrate stable state with its temperature and pressure provides an opportunity to derive the thickness with the geothermal method. Based on the latest geothermal dataset, we calculated the thickness of the gas hydrate stability zone (GHSZ) in the north continental margin of the South China Sea. Our results indicate that the thicknesses of gas hydrate stability zone vary greatly in different areas of the northern margin of the South China Sea. The thickness mainly concentrates on 200–300 m and distributes in the southwestern and eastern areas with belt-like shape. We further confirmed a certain relationship between the GHSZ thickness and factors such as heat flow and water depth. The thickness of gas hydrate stability zone is found to be large where the heat flow is relatively low. The GHSZ thickness increases with the increase of the water depth, but it tends to stay steady when the water depth deeper than 3 000 m. The findings would improve the assessment of gas hydrate resource potential in the South China Sea.

**Key words:** gas hydrate, thickness of stability zone, heat flow, continental margin, South China Sea

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### 1 Introduction

Gas hydrates are natural occurring, crystalline, ice-like substances composed of gas molecules (methane, ethane, propane, etc.) held in a cage-like ice structure. With certain physical and chemical properties that are different from the traditional hydrocarbon reservoirs, gas hydrates are preserved only under specific temperature-pressure conditions as having been discovered in the sediments in the continental margins and the arctic permafrost zones (Klauda and Sandler, 2005; Matsumoto et al., 2011). Owing to the unique structure, broad distribution, large scale and shallow burial depth in existence, gas hydrate is considered as a favorable substitute of the fossil fuels in the 21st century with a particular potential to become a clear energy with no pollution after combustion. The latest estimation for the amount of gas hydrate worldwide is ca.  $1.5 \times 10^{16}$ – $2.1 \times 10^{16}$  m<sup>3</sup> (Milkov, 2004; Mako-gon, 2010), which is twice as the total amount of the coal, oil and gas resources available and will serve as an energy resource to the mankind for at least a thousand years.

Given its high content of methane, the gas hydrate is also an unstable carbon reservoir in the shallow earth, serving as a mod-

ulator of climate change, and plays a vital role in the carbon exchange between the lithosphere, atmosphere and hydrosphere. As a greenhouse gas, the methane contained in the gas hydrate would intensify the global warming effect if released without control and thus would influence the global climate change significantly (Wu et al., 2003; Ruppel, 2011). Gas hydrate mainly occurs in the shelf and slope areas of the continental margins, where the marine engineering activities are available. Considering the subtle instability of the gas hydrates, any small changes in the temperature and pressure conditions would induce the decomposition of the gas hydrates of the area concerned; the gas released from this decomposition, would affect the structure and consolidation of the marine sediments. In addition, the change in the formation pressure would trigger collapses of the slopes, possibly resulting in a local earthquake or tsunami as well (Wang et al., 2005a). Accordingly, the mentioned resource and environmental effects of the gas hydrate have evoked considerable attention in the areas of both geoscience community and industry.

Recently, with the increasing shortage of global fossil fuels, each country in the world has extended the investigation on the

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gas hydrates that occurred in the seafloor sediments and in land. Since the first discovery of natural gas hydrate in the permafrost zones in the Messoykha gas field of the Western Siberia in Russia in 1965, a large number of studies have been undertaken widely with the aid of geophysical, geochemical and other technologies available to explore the gas hydrates. The gas hydrates are found predominately in the marine sediments of the continental margins, approximating to 95%–98%, whereas only very limited occurrence in the permafrost zones (~2%) (Birchwood et al., 2010; Ruppel, 2011). Among the technologies available for gas hydrate exploration, the recognition of Bottom Simulating Reflectors (BSRs) on the seismic profiles has provided key clue for the existence of gas hydrate in the shelf sediments. In addition, an increasing number of geophysical and geochemical anomalies have been found as an index for the potential appearance of gas hydrate deposits, leading to the discovery of gas hydrate deposits in over 230 sites (Makogon, 2010).

Although the exploration of gas hydrates in China was initiated late compared with other countries in the world, much progress has been made in recent years. The first natural gas hydrate sample, which was obtained in Shenhu area (south of the Zhujiang River (Pearl River) Mouth Basin, ZRMB) of the north continental margin of South China Sea (SCS) in 2007, set China to the fourth place in the world in terms of the availability of sampling natural gas hydrate only after USA, Japan and India. Subsequently, natural sample of gas hydrate in land was firstly retrieved in the permafrost zone of Qilian, west China in 2009. More recently, the gas hydrate sample of high-purity has been drilled for the first time in the offshore area east of the ZRMB, northern SCS in 2013. These discoveries described above indicate great potential of gas hydrate resources in the SCS.

As a fairly important index to assess the resource potential, the thickness of the gas hydrate stability zone (GHSZ) has attracted much attention in the past decades. Depths of the BSRs from the seismic profiles are commonly considered as an approximate thickness of GHSZ (Markl et al., 1970; Shipley et al., 1979; Holbrook et al., 1996; Song et al., 2002; Zhang et al., 2012; Luo et al., 2013). Although the estimation of the stability zone thickness by this seismic manner is direct and accurate, the data is not available universally, as a result of the limited coverage of seismic profiles in target area. However, considering the critical requirements of temperature and pressure condition for the stability of gas hydrate, it will be useful to grasp a good knowledge of the pressure, temperature and geothermal regime of the prospective reserve regions of gas hydrate in the search of the potential reserve of gas hydrate. The geothermal method has been proposed and applied worldwide to analyze the thickness of the stability zone of the gas hydrate with the aid of equilibrium state for the stable phase of the gas hydrate (Yamano, 1982; Davis et al., 1990; Handa, 1990; Dickens and Quinby-Hunt, 1997; Zatsepina and Buffett, 1997; Sloan, 1998; Bishnoi and Dholabhai, 1999; Golmsh-tok et al., 2000; Grevemeyer and Villinger, 2001; Sain et al., 2011; Zhang et al., 2011).

Unfortunately, considerable uncertainties are involved with the resultant thicknesses of GHSZ and the predicted reserves of gas hydrate from the previously numerous geothermal investigations in SCS because of the poor data coverage and lack of identified key parameters (e.g., Chen et al., 2004; Ge et al., 2006; Xu et al., 2010). With the expansion of oil and gas exploration in the offshore area of the northern margin of the SCS, a great deal of data has been obtained in the past decade. Therefore, it is necessary and feasible to update all the geothermal data available to recalculate the thickness of GHSZ in the northern margin of the SCS.

In this study, we compiled all the heat flow data in northern SCS, with the identified reliable thermal properties, providing a reasonable estimate of gas hydrate stability zone thickness. We then discussed in detail the factors that would possibly influence the spatial pattern of GHSZ thickness.

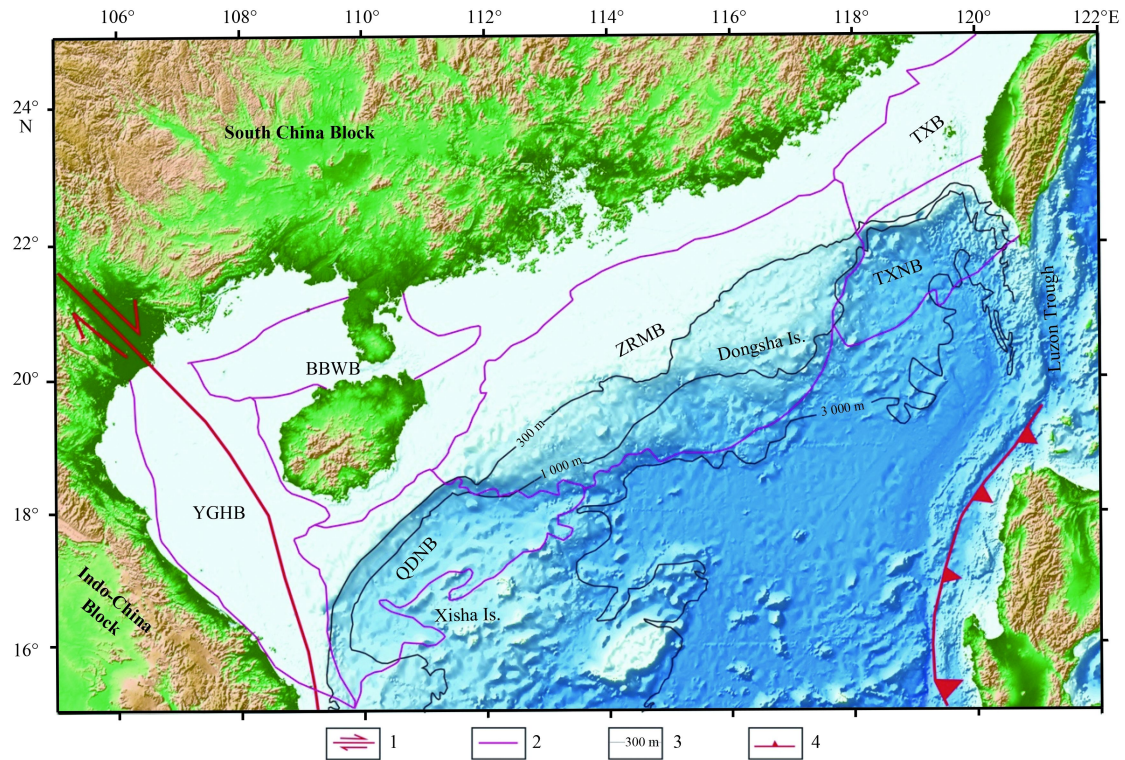
## 2 Geological settings

The South China Sea (SCS), the largest marginal sea in the western Pacific region with an area of  $\sim 350 \times 10^4$  km<sup>2</sup>, is located at the joints of the Eurasian Plate, the Pacific Plate and Indian Ocean Plate. The tectonic evolution of the SCS is affected by the interactions between these three plates since the Cenozoic (Sun et al., 2006; Wei et al., 2012). In spite of controversies for the opening mechanisms of SCS, the opening time is well constrained as around 33 Ma and the seafloor spreading ends at 16–15 Ma (Sun et al., 2006; Li et al., 2014). In addition, a large number of Cenozoic extensional sedimentary basins have been developed on the northern shelf areas of the SCS (Fig. 1). From west to east, they are arranged as the Yinggehai Basin (YGHB) (located between the Hainan Island and Vietnam coast), the Qiongdongnan Basin (QDNB) (south of the Hainan Island), the ZRMB, the Taixinan Basin (TXNB) and Taixi Basin (TXB) (west of the Taiwan Island) severing as the major oil and gas resources in the offshore areas of China.

Three sets of source rocks, including the Eocene lacustrine facies mudstones, the Oligocene onshore and swamp facies coal formation and the Miocene marine mudstones have been distinguished in these sedimentary basins along the northern SCS (Yang et al., 2000; Wei et al., 2012). These source rocks are now under mature-overmature stage thanks to high geothermal regime, enabling sufficient gas source for the formation of gas hydrates in the northern shelf and slope area of the SCS. Biogenic gas has been found in the shallow water shelf area and deep water slope area in the north SCS, mainly distributed in the basins of the YGHB, QDNB and ZRMB, with a depth of 200–2 300 m (Yu et al., 2014).

As described above, interactions between multiple plates around the SCS induce diverse tectonic deformation, resulting in the complicated geomorphic pattern in the seafloor of SCS. These processes also generate complex systems of faults and fractures, through which deep-sourced fluids and gases migrate and ultimately reach the seafloor in the hydrocarbon vents. The topography of the shelf area in the northern SCS is fairly flat whereas extremely complex in the slope area. Various geomorphic units, including the deep-sea trough, seafloor plateau, platform and steep slopes and submarine fan, are discovered by all kinds of marine exploration technologies, which provide favorable geological condition for the formation of gas hydrates and their preservation (Yu et al., 2004, 2014; Wu et al., 2004; Shyu et al., 1998; Lüdmann, 2001).

Most of the northern slope area of the SCS is characterized by gravity flow and pelagic sedimentation (Yu et al., 2004; Sha et al., 2009). The sediment owns a moderate sand content and a relatively large density along with sufficient porous space. The favorable porosity and permeability of sediment in the north of SCS offers a perfect condition for gas hydrates accumulation (Yu et al., 2004, 2014; Zhang et al., 2006). The Cenozoic crustal thinning and extension contribute to the high geothermal regime for the north of SCS (Shi et al., 2003; Jin et al., 2004; Mi et al., 2009), providing sufficient heat for the generation of the gas hydrates. In a word, previous explorations in the SCS have illustrated that the northern continental margin of the SCS is one of the best prospective targets for gas hydrates in China (Wang and Wang, 2005;

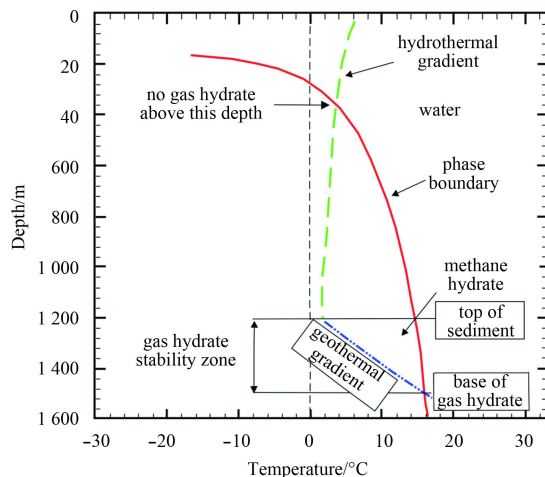


**Fig. 1.** Sketch showing the tectonic framework and basin distribution in the northern continental margin of the South China Sea. YGHB represents Yinggehai Basin, BBWB Beibuwan Basin, QDNB Qiongdongnan Basin, ZRMB Zhujiang River Mouth Basin, TXNB Taixinan Basin, and TXB Taixi Basin. 1 represents the Red River Strike-slip Fault, 2 basin boundary, 3 contour of water depth, and 4 subduction zone.

Wang et al., 2009; Zhang et al., 2006, 2007, 2012; Wu et al., 2003; Wei et al., 2012; Liu et al., 2012).

### 3 Methods and data

The unique, cage-like, structure of the gas hydrates requires low temperature and high pressure conditions to keep a steady state. The gas hydrate stability zone is defined here as the gas hydrates reserve zone in the favorable temperature and pressure conditions. As shown in Fig. 2, this area is entrapped by the phase diagram of gas hydrate, the geothermal gradient curve and



**Fig. 2.** Sketch of the temperature and pressure-dependent stability zone of methane hydrate (modified from Sain et al., 2011).

the seafloor together. The thickness of the gas hydrate stability zone is defined as the distance between the seafloor and the base of gas hydrate, which is determined by the intersection of the phase diagram and the geothermal curve. In return, heat flow can be used to constrain the thickness of the gas hydrate stability zone.

#### 3.1 Methods

The temperature and pressure dependent phase equation of the gas hydrate has been utilized to calculate the stability zone thickness (e.g., Handa, 1990; Dickens and Quinby-Hunt, 1997; Zatsepina and Buffett, 1997; Sloan, 1998; Bishnoi and Dholabhai, 1999; Jin et al., 2005; Wang et al., 2005b, 2009; Wang and Wang, 2005). The parameters involved are generally various for different scholars, given the variations in chemical component of specific gas hydrates, geological and geophysical settings of the areas of interest. Nevertheless, it is generally accepted that the resource potential of the gas hydrates is related to a series of factors, such as the water depth, salinity, porosity of the sediments, gas origin, seafloor temperature, and geothermal gradient, etc. Given the geological settings of the northern continental margin of the SCS, the phase equation of the gas hydrate proposed by Dickens and Quinby-Hunt (1994) is applied and introduced as follows:

$$\frac{1}{T} = 3.79 \times 10^{-3} - 2.83 \times 10^{-4} \lg P, \quad (1)$$

where  $T$  is the temperature (K),  $P$  is the pressure (MPa). In addition, the pressure  $P$  can be calculated as

$$P_1 = P_0 + \rho_1 g z_0 \times 10^{-6}, \quad (2)$$

$$P_2 = P_0 + g(\rho_1 z_0 + \rho_2 z) \times 10^{-6}, \quad (3)$$

where  $P_1$  is the hydrostatic pressure (MPa),  $P_0$  is the atmospheric pressure with the value of 0.101 325 MPa,  $\rho_1$  is the seawater density (average as 1 035 kg/m<sup>3</sup>),  $g$  is the gravity accretion (9.8 m/s<sup>2</sup>),  $z_0$  is the depth of seawater (m),  $P_2$  is the lithostatic pressure (MPa),  $\rho_2$  is the density of the sediments (kg/m<sup>3</sup>), and  $z$  is the GH-SZ thickness (m). Among them,  $P_2$  is the sum of  $P_1$  and pressure derived from the gas hydrate thickness.

Temperature is obtained by the formula as followed:

$$T = T_0 + z \times G, \quad (4)$$

$$Q = K \times G, \quad (5)$$

where  $T$  is the temperature at the depth of  $z$ ,  $K$  is the average thermal conductivity of the gas hydrate bearing sediments (W/(m·K)),  $T_0$  is the seafloor temperature,  $G$  is the average geothermal gradient, and  $Q$  is the heat flow (mW/m<sup>2</sup>).

For one specific site where the geothermal parameters, such as the heat flow, thermal conductivity and seafloor temperature ( $T_0$ ), are available, the GHSZ thickness  $z$  then can be obtained with the iteration of Eqs (1)–(5) described above.

### 3.2 Data

As mentioned above, certain fundamental parameters, such as the water depth, geothermal gradient, thermal conductivity, are needed for calculating the GHSZ thickness. With the demand of oil and gas exploration in the basins of the northern continental margin of the South China Sea, a large number of boreholes have been drilled, providing abundant new geothermal data. In this study, we combined all the formation temperature data and thermal properties available in the northern area of the SCS from previous studies (He et al., 2001; Shi et al., 2003; Mi et al., 2009; Zhang et al., 2011; Tang et al., 2014; Wang et al., 2014) with our new data from the QDNB and YGHB. With the updated geothermal data in the northern continental margin of the SCS, the coverage and quality of data have been improved a lot.

Thermal conductivity is a key parameter in thermal calculation. Considering that the gas hydrate sample is rare and valuable in the SCS, no specific thermal conductivity data of the gas hydrate has been reported in the literatures till now. In this study, alternatively we used the thermal conductivity data of the borehole sediments from the SCS (Fig. 3). The thermal conductivities range from 0.60 to 2.0 W/(m·K), with a mean value of 1.17 W/(m·K). This value approximates to the measured conductivities

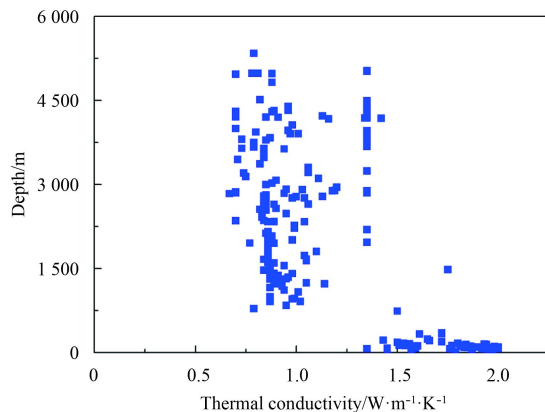


Fig. 3. Distribution of thermal conductivity in the north continental margin of SCS.

of the gas hydrate bearing sediments from other continental margins in the world. For instance, Kim and Yun (2013) reported 1.47 W/(m·K) for the samples from the Ulleung Basin, the East Sea. The measured and modeled values for the synthesized methane dominative hydrate bearing sediments vary from 0.90 to 1.13 W/(m·K) (Waite et al., 2002; Huang and Fan, 2005). In addition, Grevenmeyer and Villinger (2001) argued that the influence of typical quantities of low-thermal-conductivity gas hydrate on the bulk thermal conductivity is insignificant and that the thermal conductivity profile between the BSR and the seabed could be approximated by a mean value. Thus, the seabed *in situ* measurements should be used instead of an empirical relationship. In this study we calculate the gas hydrate stability zone thickness in the SCS with the thermal conductivity data from the borehole sediments.

Geothermal gradient is another important parameter to investigate the geothermal regime of the sedimentary basins. In this study, more than 1 000 geothermal gradient data have been compiled from both previous studies and this study (He et al., 2001; Shi et al., 2003; Xu et al., 2006, 2012; Li et al., 2010; Zhang et al., 2011; Wang et al., 2014; Tang et al., 2014) (Fig. 4), to calculate the depth of the base of the gas hydrate stability zone. It is noted that the geothermal gradient varies from 0.020°C/m to 0.140°C/m, with a mean value of 0.062°C/m, which is apparently larger than the other typical sedimentary basins in China. It is also this high geothermal regime that makes the northern shelf and slope areas of the SCS good gas hydrate reservoirs.

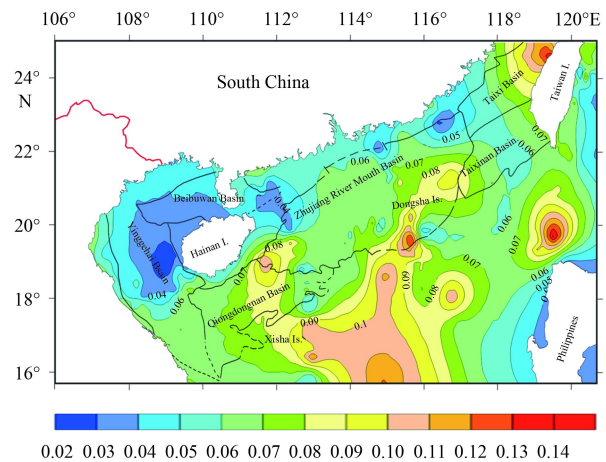
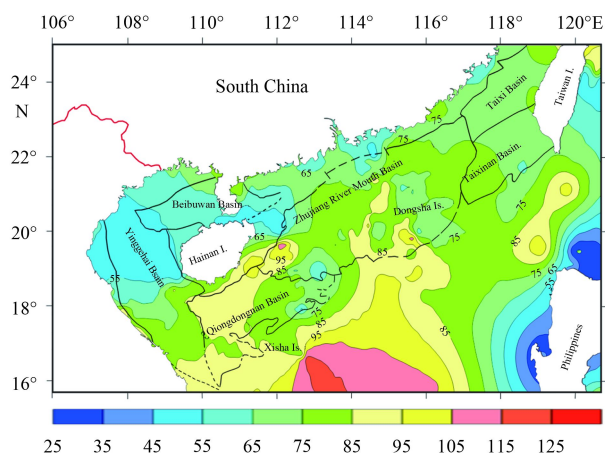


Fig. 4. The distribution of geothermal gradient (°C/m) in northern continental margin of the SCS.

Heat flow is a geophysical parameter to assess the geothermal regime of the concerned area. The value is the product of geothermal gradient multiplying the thermal conductivity. A great deal of heat flow data has been obtained in the SCS recently from the numerous explorations of hydrocarbon and surveys of marine heat flow. For certain site, the geothermal gradient can be determined if the heat flow and thermal conductivity data there are available, vice versa. Here, we combined the previous heat flow data available (He et al., 2001; Shi et al., 2003; Xu et al., 2006, 2012; Li et al., 2010; Zhang et al., 2011; Wang et al., 2014; Tang et al., 2014) with our new data from the Qiongdongnan Basin and Yinggehai Basin, to calculate the gas hydrate stability zone thickness. The spatial pattern of heat flow in the northern margin of the SCS is presented as Fig. 5. Heat flow in the north margin of the SCS mostly falls within the range of 40–120 mW/m<sup>2</sup>, with a



**Fig. 5.** Spatial distribution pattern of heat flow ( $\text{mW}/\text{m}^2$ ) in northern continental margin of the SCS.

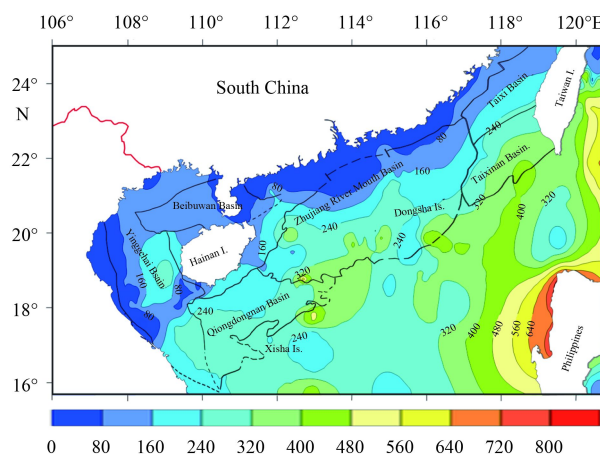
mean value of  $79 \text{ mW}/\text{m}^2$ . Among them, high heat flow values are found in the Yinggehai Basin, west of the Hainan Island, the Taixi Basin and parts of the Taixinan Basin, nearby the Taiwan Island, along with the Central oceanic basin. Low heat flow areas are present in the Beibuwan Basin, northern Qiongdongnan Basin, eastern Zhujiang River Mouth Basin, and the Luzon Trough in the east.

Water depth from previous studies (Jin et al., 2004; Ge et al., 2006; Zhang et al., 2011, either from the measurements on the basis of heat flow determination during the cruises or NOAA database) is combined with the data collected in this study (from oil and gas boreholes). The water depth in the northern continental margin of the SCS varies from around tens to hundreds of meters in the shelf area to thousands of meters in the oceanic basins, and approximates to 800 m for the main sedimentary basins. The trend of the contour of water depth is parallel to the coast.

Seafloor temperature is indispensable for determining the geothermal gradient and heat flow in geothermal studies. We collected all the seafloor temperature available from previous heat flow determinations (Nissen et al., 1995; Xu et al., 2006; Li et al., 2010; Xu et al., 2012). However, the seafloor temperature data is still insufficient in coverage and certain empirical relationship has been introduced here to calculate the seafloor temperature. The seafloor temperature in the SCS varies from  $6\text{--}14^\circ\text{C}$  in the shelf area,  $2\text{--}6^\circ\text{C}$  in the slope area and around  $2^\circ\text{C}$  in the central oceanic basin, generally higher than the Japan Sea but lower than the Indian marginal sea (Wang et al., 2005a). Feng et al. (1996) proposed that the seafloor temperature in the SCS decreased with the increasing water depth and that tended to be constant at about  $2.2^\circ\text{C}$  when the water depth was larger than 2 800 m. Xue and Huo (1991) also discussed the relationship between the seafloor temperature and water depth in four seasons of the SCS. Yuan (2007) constructed an empirical relationship with the data from Xue and Huo (1991) and Feng et al. (1996), which is applied to determine the seafloor temperature in the SCS in this study.

#### 4 Results

We integrated the thickness of the gas hydrate stability zone for the northern margin of the SCS calculated with the methods described above with the Kriging interpolation technology in the Surfer software, the resultant spatial distribution pattern of the gas hydrate stability zone thickness in the north SCS is presented as Fig. 6.



**Fig. 6.** The thickness (m) distribution of gas hydrate stability zone in northern continental margin of SCS.

Most of the northern shelf and slope areas of the SCS are favourable for the formation and preservation of the gas hydrates. The calculated thickness of the stability zone varies much for different areas, mainly concentrating on the range of 200–300 m. Generally, relatively large thickness ( $\sim 400 \text{ m}$  or more) is found in the northeastern Xisha Island, the Taixinan Basin, southeastern Dongsha Island and the Luzon Trough; whereas the low thickness (0–100 m) is observed in the areas with shallow water depth, usually less than 500 m, such as the Yinggehai Basin, the northern Zhujiang River Mouth Basin, and the Taixi Basin.

Sedimentary basins in the northern margin of the South China Sea have different gas hydrate stability zone thicknesses. For instance, the thickness in the QDNB is relatively large, ranging from 5 m to 560 m, with a mean of 180 m; while for the ZRMB, it varies from 1 m to 400 m, and the average thickness is about 110 m. The thickness in the YGHB is less than 140 m, with an average thickness about 50 m.

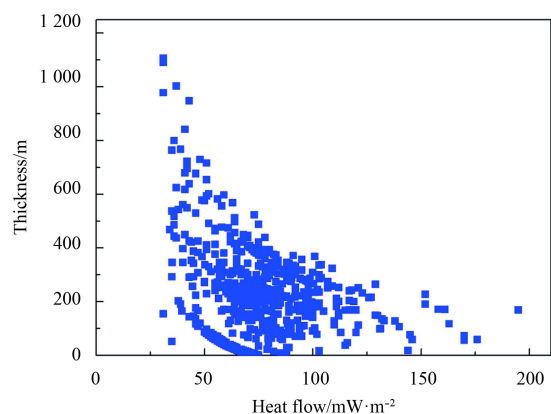
In addition, the trend of the contour of the gas hydrate stability zone thickness is generally parallel to the strike of the continental slope. With the increase of water depth, the stability zone thickness increases as well. The thickness in the continental shelf area is less than 150 m, with a mean of 100 m, and then become larger for the slope and oceanic basins, ranging from 200 m to 800 m, with an average of 350 m. The prospective areas with large thickness are band-like in the eastern sub-oceanic basin and southwest sub-oceanic basin. As for the areas with shallow water depth ( $<300\text{--}500 \text{ m}$ ), the gas hydrate is speculated to be hard in stability, owing to very low lithostatic pressure.

#### 5 Discussion

##### 5.1 The influence of heat flow on the GHSZ thickness

Heat flow displays a remarkably negative correlation with the GHSZ thickness, as presented in Fig. 7. With the increasing heat flow, the GHSZ thickness reduces gradually, implying that relatively low heat flow is favourable for gas hydrate preservation. For instance, for the GHSZ thickness of 200–400 m, the heat flow is  $50\text{--}100 \text{ mW}/\text{m}^2$  in the SCS, in agreement with our recent compilation of geothermal regime of the continental margins where the gas hydrates are available in the world (Lei et al., 2013).

As mentioned above, the preservation of gas hydrates is closely related to the temperature condition. When the geothermal gradient increases, the area entrapped by the phase boundary diagram and geothermal gradient curve is reduced ac-



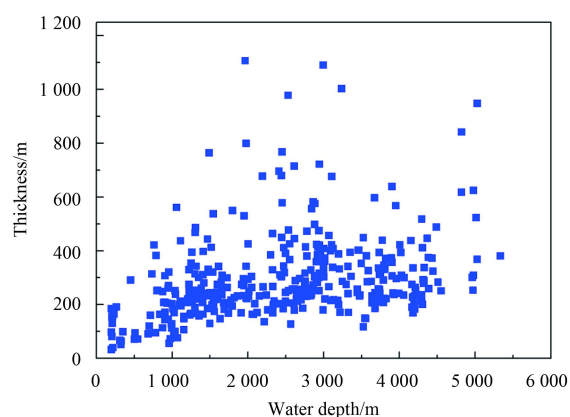
**Fig. 7.** Sketch showing the relationship between the GHSZ thickness and heat flow.

cordingly (Fig. 2), which means a decrease of GHSZ thickness as well, and vice versa. The sedimentary environment in the northern shelf and slope areas of the SCS stays steady and the sedimentary facies exhibit little variations, indicating a relatively consistent thermal conductivity. Therefore, the heat flow in this area varies with the change of the geothermal gradient. The geothermal regime determines the preservation of gas hydrates. Conclusively, relatively low heat flow could be taken as an indicator of the gas hydrate target.

### 5.2 The influence of water depth on the GHSZ thickness

Pressure is another factor that influences the gas hydrate stability zone. As illustrated in Fig. 8, the relationship between the GHSZ thickness and water depth is not unchangeable. The thickness of the GHSZ increases with the increasing water depth from the surface until the depth 3 000 m. The GHSZ thickness then stays constant without changing with the increasing water depth in the region deeper than 3 000 m.

This observation is speculated to be the products of the coupling temperature and pressure effects on the gas hydrates stability. For one thing, the hydrostatic and lithostatic pressures increase naturally with the increasing water depth, enabling the gas hydrates to keep stable. At meanwhile, the seafloor temperature decreases with the increase of water depth, and low temperature is favorable for the preservation of gas hydrates; however, the temperature would tend to be constant (2–4°C) if the water depth



**Fig. 8.** Sketch showing the relationship between the thickness of gas hydrate stability zone and water depth in the north continental margin of the SCS.

reaches a critical depth (Xue and Huo, 1991; Yuan, 2007). Under this circumstance, the geothermal gradient no longer shows a significant relationship with the water depth, and the influence of pressure on the GHSZ thickness becomes insignificant, which could explain the observed nearly constant GHSZ thickness where the water depth exceeds 3 000 m.

### 5.3 Comparison with previous results

The spatial pattern of the GHSZ thickness of our results shares similarity with Ge et al. (2006) and Xu et al. (2010), yet the value from this study is somewhat larger than those from Ge et al. (2006) and Jin et al. (2005), which is likely to be caused by some bias of the thermal conductivity, geothermal gradient and pressure data involved in their studies. On one hand, the geothermal gradient would be large if a low thermal conductivity was considered, leading to the low GHSZ thickness. For instance, Xu et al. (2010) used a constant thermal conductivity (1.00 W/(m·K)), whereas 1.17 W/(m·K) is assigned for the thermal conductivity value in our analysis. Ge et al. (2006) used one constant geothermal gradient (0.060°C/m) in their calculation, while the geothermal gradient in the northern SCS varies from 0.020 to 0.140°C/m in this study. A constant geothermal gradient would mask some detailed variation in the GHSZ thickness. On the other hand, these authors considered only the hydrostatic condition in the pressure calculation, neglecting the influence from the underlying sediments, which would cause an underestimated GHSZ thickness. Accordingly, both processes would account for the resultant low GHSZ thickness in previous results.

In addition, the BSR derived thickness from the seismic profiles provides an independent verification for the results here. He et al. (2009) proposed the GHSZ thickness would be 230 m in the Xisha Trough utilizing a heat flow of 93 mW/m<sup>2</sup>. The average GHSZ thickness in this area is estimated to be around 350 m by seismic data (Wu et al., 2005). In this study, the thickness there would be around 297 m, when taking the measured heat flow of 83 mW/m<sup>2</sup> into consideration, instead of the value used by He et al. (2009). Thus, all the data sets, as outlined above, can generally be compared with each other. Furthermore, Wu et al. (2005) identified a stability zone thickness by BSR as 150 m in the offshore area near the Dongsha Island, while the thickness is about 170 m in our geothermal analysis.

However, it should be mentioned that all the GHSZ thickness for the SCS reported here are estimated only based on the temperature and pressure conditions, without taking the other factors into account. Actually, besides the temperature and pressure conditions, the sedimentation and gas source are also important for the gas hydrate formation and preservation. For instance, the GHSZ thickness can reach up to 800 meters in the Luzon Trough, due to its relatively low geothermal condition. However, if the sediments and gas source there are not available, the gas hydrate could be unavailable as well. So the specific geological condition should be considered when assessing the gas hydrate potential of the concerned target. Moreover, the GHSZ thickness predicted here is only the theoretical value, which means it is the maximum thickness. The gas hydrate encountered during the drilling in the northern SCS is found to be interbedded within the sediments, and the actual thickness is then less than the predicted one by BSR and/or geothermal approaches.

## 6 Conclusions

With the updated geothermal data in the northern margin of the SCS, the gas hydrate stability zone thickness and spatial dis-

tribution pattern are investigated in this study. Some conclusions are summarized as follows:

The temperature and pressure conditions are commonly suitable for gas hydrates formation and preservation in the majority of the shelf and slope area of the northern SCS. Yet, the gas hydrate stability zone thickness varies in space. The GHSZ thickness mainly concentrates on the range of 200–300 m, with the maximum of ~800 m localized in the Luzon Trough. The thickness derived from geothermal data corresponds well with that from the seismic derived BSR base depth.

The spatial distribution of the GHSZ thickness in the northern margin of the SCS tends to be parallel to the strike of the coast, in the shelf and slope areas with a water depth larger than 300 m. For those areas where the water is less than 300 m deep, the hydrostatic pressure is too low to maintain the gas hydrate stability.

The GHSZ thickness is influenced by heat flow and water depth. The thickness is larger in the areas where the heat flow is lower and the water depth is larger, whereas it tends to be constant when the water is deeper than 3 000 m as a result of the coupling effects of temperature and pressure.

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