Depositional characteristics and accumulation model of gas hydrates in northern South China Sea

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Article history:
Received 13 June 2013
Received in revised form 13 March 2014
Accepted 17 March 2014
Available online 26 March 2014

Keywords:
Northern South China Sea
Gas hydrate
Bottom simulating reflectors (BSRs)
Gas hydrate stability zone (GHSZ)
Depositional accumulation model

Abstract
The South China Sea (SCS) shows favorable conditions for gas hydrate accumulation and exploration prospects. Bottom simulating reflectors (BSRs) are widely distributed in the SCS. Using seismic and sequence stratigraphy, the spatial distribution of BSRs has been determined in three sequences deposited since the Late Miocene. The features of gas hydrate accumulations in northern SCS were systematically analyzed by an integrated analysis of gas source conditions, migration pathways, heat flow values, occurrence characteristics, and depositional conditions (including depositional facies, rates of deposition, sand content, and lithological features) as well as some depositional bodies (structural slopes, slump blocks, and sediment waves). This research shows that particular geological controls are important for the presence of BSRs in the SCS, not so much the basic thermodynamic controls such as temperature, pressure and a gas source. Based on this, a typical depositional accumulation model has been established. This model summarizes the distribution of each depositional system in the continental shelf, continental slope, and continental rise, and also shows the typical elements of gas hydrate accumulations. BSRs appear to commonly occur more in slope-break zones, deep-water gravity flows, and contourites. The gas hydrate-bearing sediments in the Shenhu drilling area mostly contain silt or clay, with a silt content of about 70%. In the continental shelf, BSRs are laterally continuous, and the key to gas hydrate formation and accumulation lies in gas transportation and migration conditions. In the continental slope, a majority of the BSRs are associated with zones of steep and rough relief with long-term alternation of uplift and subsidence. Rapid sediment unloading can provide a favorable sedimentary reservoir for gas hydrates. In the continental rise, BSRs occur in the sediments of submarine fans, turbidity currents.

1. Introduction
Gas hydrates, also known as methane clathrates or clathrate hydrates, are ice-like solid substances formed by water and gas under conditions of low temperature and high pressure (Kvenvolden, 1993; Sloan and Koh, 2008). Over the past two decades, many countries have carried out investigation and evaluation programs on gas hydrates (Matsumoto et al., 2011; Sain and Gupta, 2012). With the implementation of the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program (IODP), and deep drilling programs, evidences of wide-spread gas hydrates have been found in many areas (Tréhu et al., 2004; Riedel et al., 2006; Collett et al., 2008; Zhang et al., 2007a; Park et al., 2008; Lee et al., 2011). Globally, gas hydrates have been identified from geophysical, geochemical and geological surveys, and by drilling and coring (Boswell and Saeki, 2010). Many investigations have been carried out in the northern part of the South China Sea (SCS), particularly in May 2007, when drilling conducted by the China Geological Survey Bureau in the Shenhu district successfully recovered gas hydrate cores from three sites (Zhang et al., 2007a; Wang et al., 2011a) (Figs. 1 and 2).

The formation, evolution, and occurrence of gas hydrates require a combination of various physical and chemical factors. Bottom simulating reflectors (BSRs) are a result of an acoustic impedance contrast between gas hydrate-bearing sediments and free gas trapped in the sediments underneath. The zone where gas hydrates are stable is called the gas hydrate stability zone (GHSZ). The sub-bottom depth of the GHSZ depends on the geothermal gradient, bottom water temperature, pressure (water depth), and gas and fluid chemistry (Kvenvolden, 1993). The high-amplitude
events of the same polarity as the seafloor reflector occurring within the inferred GHSZ, are highly prospective indicators for gas-hydrate-bearing sands (Saeki et al., 2008). However, some studies have suggested that the base of the gas hydrate does not always coincide with the base of the GHSZ (Xu and Ruppel, 1999; Diaconescu et al., 2001; Zhang et al., 2011), and that gas hydrates are always in a process of dynamic equilibrium. In addition, there are always many uncertainties if only BSRs are used to evaluate the development and distribution of gas hydrates. The control factors on BSRs are not the same thing as the control factors on the

![Figure 1](image1.png)

**Figure 1.** (a) Location map showing the area of gas hydrate exploration in the Pearl River Mouth Basin, the northern South China Sea. The water depth of northern continental slope ranges from 200 to 4400 m. The base map is from Chen and Wen (2010); (b) Bathymetric map of Shenhu drilling district, red dots show cored samples with gas hydrate (site A, B and C) and purple dots show cored samples with no gas hydrate. The water depth ranges from about 800 to 1700 m. The submarine geomorphy consist of several sea valleys. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

![Figure 2](image2.png)

**Figure 2.** Decomposition of gas hydrate cores in Shenhu drilling district of SCS. (a) Site A; (b) Site C.
occurrence of gas hydrate. Recent studies have shown that BSRs are not always good indicators of concentrated methane-hydrate occurrences and cannot be used to accurately predict in-situ methane-hydrate volumes (Tsujii et al., 2009), and there can be an obvious disconnect between gas hydrate accumulations and the presence of BSRs (Riedel et al., 2006; Collett et al., 2008; Frye et al., 2010; Matsumoto et al., 2011; Shedd et al., 2012). BSRs in the northern continental slope of the SCS show high amplitude and negative polarity, and are laterally continuous and approximately parallel to the seafloor. Because BSRs follow a thermobaric surface rather than a structural or stratigraphic interface, they are normally observed to crosscut other reflectors (Shipley et al., 1979). BSRs represent the interface between the GHSZ and the underlying sediments containing free gas. In fact, a small amount of gas in the pore spaces of sediments can cause a decrease in P-wave velocity and form a strong seismic reflection. In addition, BSRs are influenced by many factors such as tectonization, sedimentation, and gas hydrate saturation; rock properties also have some influence on seismic attribution (Tang et al., 2011).

Currently, the gas hydrate accumulation system is the subject of much research, and several accumulation models have been established (Borowski, 2004; Freire et al., 2011). However, most of these studies are from the perspective of temperature, geological structure, and pressure (Ginsburg and Solovev, 1990; Milkov and Sassen, 2002; Bünz et al., 2003; Wang et al., 2008a; Yang et al., 2010). Overall, research on the characteristics of and models for deposition and accumulation of gas hydrates is still relatively weak because of a lack of comprehensive consideration of the combined effects of a variety of geological processes and the physical and chemical factors involved in the accumulation process (Lu et al., 2008). A comprehensive analysis of accumulation systems combined with hydrocarbon gas supply, hydrocarbon gas migration pathways, gas hydrate occurrence and distribution controlled by rock formations, and tectonization has not yet been conducted in the SCS.

2. Geological setting and data

There are three major basins on the northern continental slope of the SCS: the Southwest Taiwan Basin, the Pearl River Mouth Basin, and the Qiongdongnan Basin. Most of the BSRs occur in four areas, the Dongsha, Shenhu, Xisha, and Qiongdongnan districts, which are located in an eastern longitudinal range of 109°00′–121°00′, a latitudinal range of 15°00′–23°00′, and have an overall northeast trend (Figs. 1 and 3). The Shenhu gas hydrate drilling area is located between the Xisha trough and the Dongsha islands in the Baiyun depression of the Zhu II sub-basin. Eight sites have been drilled, and gas hydrate cores were successfully recovered at sites A, B, and C (Figs. 1 and 2).

Previous research has shown that gas hydrates occur in surface sediments on continental slopes and oceanic rises and in deep-water basins of marginal seas. The SCS is the largest marginal sea in the western Pacific Ocean, and its northern continental margin belongs to a passive continental margin. This continental margin has the common features of passive margins as well as unique characteristics (Zhu et al., 2012), because its formation and evolution was influenced by interactions with the surrounding plates since the Mesozoic, and also by geodynamic events such as the extension and fracturing of the SCS. It has suitable conditions for gas hydrate accumulation and favorable exploration prospects (Yu

Figure 3. Distribution of mapped BSRs in each sequence and the contour of heat flow value in northern continental slope, SCS. The BSRs plane distribution is provided by Guangzhou Marine Geological Survey. BSRs number: 1–10, sequence II; 11–20, sequence III; 21–26, sequence I. The contour of heat flow distribution is according to Zhang et al. (2011). The heat flow range in the BSR area is within 65–90 Mw/m², and mainly between 75 and 85 Mw/m².
Sequence stratigraphy is a methodology based on relative sea-level changes that provides a framework for the elements of any depositional setting, thus facilitating paleogeographic reconstructions and the prediction of facies and lithologies (Catuneanu et al., 2011). Using a sequence stratigraphic framework, the spatio-temporal evolution of depositional systems can be revealed and interpreted, and further guidance on depositional and accumulation characteristics of gas hydrates in the SCS can be obtained, which is of great significance.

Subdivision of the stratigraphic sequences in Shenhu district indicated that the tectonic movements, which affected relative sea level changes had occurred in the SCS since the Miocene. This paper made reference to the relative sea level changes in the Yinggehai—Qiongdongnan Basin and the Pearl River Mouth Basin to identify three sequence boundaries (T3, T2, T1) in the northern continental slope of the SCS since the late Miocene. These boundaries correspond to the times 11.6, 5.33, and 1.81 Ma, respectively (Wang et al., 2011b; Kuang and Guo, 2011). The three corresponding third order sequences have been named as follows: Sequence III, Sequence II, and Sequence I (Fig. 4).

3. Result

3.1. Thermodynamic and sedimentary conditions for gas hydrate occurrence

In the study area, the water depth ranges from 200 to 4400 m, and the seafloor temperature is about 1–5 °C. The geothermal gradient is between 20 °C/km and 70 °C/km for strata deposited since the late Miocene. Both a decrease in the geothermal gradient and an increase in the water depth cause an increase in the thickness of the hydrate stability field (Wu et al., 2005). Taking site A in the Shenhu drilling district as an example, the seafloor water depth is about 1232 m with a seafloor temperature of 3.92 °C, and the geothermal gradient is about 48 °C/km from borehole data; therefore, the theoretical thickness of the GHSZ is about 278 m in the case of pure methane. However, the burial depth of the gas hydrate-bearing layer confirmed through well log and core data is 191–225 m below the seafloor, whereas the thickness is only 34 m (Fig. 5). As heat flow is a direct “window” for understanding the thermal state of the margin sea, many heat flow studies have been carried out in the SCS (Yuan et al., 2009; Mi et al., 2009; Zhang et al., 2011). In particular, in recent years, many heat flow values have been measured while carrying out surveys of gas hydrates and petroleum (Mi et al., 2008; Yuan et al., 2009). The present geothermal field in the deep-water area of the northern SCS is characterized by a hot basin (Mi et al., 2009). The “uniform geothermal gradient” increases with direction, from the continental shelf to the continental slope of the northern margin of the SCS (Yuan et al., 2009). The heat flow range in the BSR distribution is

![Figure 4. Sequence division, sedimentary and tectonic evolution of SCS since the Miocene. The strata can be divided into three third order sequences since the late Miocene.](image)

![Figure 5. Temperature—pressure scatter diagram and phase equilibrium curve in BSRs distribution regions of SCS. Though most of the data focused on the equilibrium curve, only little part of the data fall into the GHSZ. The main factors leading to the discrepancy were parameters uncertainties, such as measurement uncertainties of heat flow, sedimentation, salinity of Seawater, gas components and fluid flow, etc (Zhang et al., 2011). The temperature—pressure data is provided by Guangzhou Marine Geological Survey of China Geological Survey.](image)
between 65 and 90 Mw/m², and a majority of the values are between 75 and 85 Mw/m² (Fig. 3). This range increases from north to south, showing the same pattern as the geothermal gradient, from the continental shelf to the slope of the northern margin of the SCS (Yuan et al., 2009). Compared with other seas that contain gas hydrates, the heat flow values are slightly higher; therefore, the GHSZ will be a slightly thinner (Jin et al., 2004).

The sedimentary conditions of the study area have previously been described as follows: (1) The gas hydrates mainly occur in relatively coarse sediments that are soft and unconsolidated, such as sandy ooze (Yu et al., 2004; Su et al., 2005); (2) Research on the geological ages of sediments has shown that most of the soft unconsolidated sediments with BSRs were formed since the Miocene, particularly in the Pliocene and the Quaternary; (3) Some research results have shown that the sediments in the GHSZ are rich in diatom fossils (foraminifera, nannofossils, and diatoms). Therefore, the main sedimentary geological conditions affecting gas hydrate accumulation of the study area are as follows: (1) Sediments with medium porosity and high permeability can provide favorable conditions for retention of pore water, thus providing a reservoir for forming gas hydrates; (2) There must be a sufficient gas supply; (3) A high deposition rate can not only provide a gas source but also makes it easy to form an undercompacted area that may constitute a good fluid migration system. These features are mainly developed in fans, deltas, and various gravity-flow depositional systems.

3.2. BSRs occurrence

By the end of 2003, 85 gas hydrate-bearing locations had been found in the oceans worldwide of which 67 places (79%) contained BSRs (Zhang et al., 2003). On the basis of recognition of BSRs in the seismic profiles of the study area (Fig. 6), 26 BSR distribution regions were identified in the northern continental slope of the SCS. These regions have markedly different areas, and are generally present in the shallow to semi-deep sea. There are 17 regions with water depths less than 2000 m, seven regions with water depth between 2000 m and 3000 m, and only two regions with water depth more than 3000 m. In terms of geographical position, most (about ten) of the BSR distribution regions occur in the Shenhui district. The Qiongdongnan and Xisha districts both have six BSR distribution regions. In the Dongsha district there are two large BSR distribution regions, both of which are located in the deep-water area of the Taiwan bank slope between the east of the Dongsha platform and the west of the Taiwan orogenic belt. However, there are no BSRs in the area of the Dongsha district. The overwhelming majority of BSR distribution regions are located in the areas with a steep seafloor, a significant terrain variation, and a long-term successive subsidence, such as the upper continental slope of the Qiongdongnan district, the Xisha district, and the eastern part of the Shenhui district. In addition, there are some BSRs distributed in regions with a relatively simple and flat topography with a water depth greater than 2000 m (Fig. 3).

4. Discussion

4.1. Gas sources

To date, the methane contained in previously known gas hydrates is mainly biogenic gas (Kvenvolden, 1995; Collett et al., 2009; Su et al., 2010). Studies on the gas source for gas hydrate accumulation in the SCS still use the “source control theory” (Xia et al., 2001; Zhang et al., 2007b; Wu et al., 2008). The types of natural gas present in the northern continental margin of the SCS are very complex (Wu et al., 2008; He et al., 2011). Biogenic gas is widely distributed from shelf shallow water to slope deep water, which are favorable sedimentary facies for the formation of biological gases. The potential resources are large, and mainly occur in the Qiongdongnan, and Pearl River Mouth basins as well as the shallow layers between 200 and 2300 m (He et al., 2011). There are three sets of hydrocarbon source rocks in the continental margin deep-water area (Zhang and Deng, 1999), and the Baiyun depression, which contains the Shenhui drilling area, mainly has two sets of deep
Figure 9. Depositional facies and sand content in each sequence of northern slope of SCS, the numbers in all those multi-colored zones are the sand-content values. In sequence III, BSRs are mostly distributed in the bathyal facies of the Xisha and Shenhu districts. BSRs are mainly distributed in areas with sand content ranges from 8% to 20%. In sequence II, BSRs occur widely in the Xisha, Shenhu, and Dongsha districts, mainly depositional systems that include deltas, turbidite fans, and slope fans. BSRs are mainly distributed in areas with low sand content ranges from 8% to 20%, whereas in the northern part, BSRs are mainly distributed in the area with a high sand content ranges from 20% to 40%. In sequence I, BSRs are only present in the Qiongdongnan district, and almost all of them are located in the delta front and prodelta sediments. (a) Sequence III; (b) Sequence II; (c) Sequence I.
source rocks including lacustrine facies mudstone of Eocene—Oligocene age and neritic—bathyal facies mudstone of Neogene age (Zhang et al., 2007b). The gas of the Shenhua drilling area has a mixed origin comprising both shallow biogenic gas and deep thermogenic gas, but mostly shallow biogenic gas (Fig. 7)(He et al., 2011; Wu et al., 2011; Liu et al., 2012).

4.2. Migration pathways

4.2.1. Faults

Exploration and scientific studies have shown that in most of the gas hydrate discovery areas worldwide there are many different levels of faults, which play very important roles in the process of gas hydrate accumulation (Wang et al., 2008a; Yang et al., 2009; Kuang and Guo, 2011). A fault can provide a channel for deep source gas to migrate upwards and accumulate under appropriate temperature and pressure conditions, thus creating appropriate structural conditions for gas hydrate formation. At the same time, most fractures in fault systems not only act as fluid migration pathways but also as reservoir spaces (Yang et al., 2009). Episodic fault activity promotes upward leakage of thermally decomposed gases and formation of gas hydrates in the stability zone (Wu et al., 2008).

4.2.2. Diapiric structures

Increase in rapid subsidence, crustal thinning, and heat flow lead to the formation of numerous submarine diapiric structures in the study area. Several studies have confirmed that the channels formed by thermal fluid diapirs and mud diapirs are upward migration pathways for gas (Ginsburg et al., 1984; Zhang et al., 2007b; Xu et al., 2009). Analyses of the occurrences of gas hydrates in the Gulf of Mexico, the Okhotsk Sea, the Black Sea, the Caspian Sea, the Mediterranean ridge, offshore Nigeria, and the Okinawa Trough have shown that gas hydrates predominantly occur near the tops of mud volcanoes or mud diapirs (Xu et al., 2009). The diapiric structures can be of various types such as turtleback-like arches, strong or weak piercings, gas chimneys, faults (or fractures), and seabed pits. Diapiric faults are structures often observed in and around diapirs (Fig. 8). The faults are probably connected with other deep-penetrating faults formed during the expulsion of shale diapirs. These may provide pathways for gas migration (Xu et al., 2009; Lei et al., 2011). Gas chimneys are characterized by low seismic amplitude, low seismic frequency, and low coherency, interpreted as being associated with the upward migration of fluids or free gas (Sun et al., 2012). They form by the combined action of overpressure, low stress, and a mud shale sealed reservoir. Gas chimneys are considered to be one of the most important structures in gas hydrate systems. On the one hand, gas chimneys illustrate the existence of a gas source (perhaps deep thermogenic gas); on the other hand, they show evidence of fluid migration channels (Sun et al., 2012). Many high-angle dendritic or flower fault structures are formed accompanying gas chimneys, and these faults can also be channels for late fluid migration (Wu et al., 2009). In addition, the high temperature and overpressure potential contained in the diapiric structures can provide the thermal power to promote the maturity of source rocks and hydrocarbon generation and can act as the driving forces for hydrocarbon migration and accumulation (He et al., 2010).

4.3. Sedimentary factors controlling the occurrence of gas hydrates and BSRs

The formation of gas hydrates is influenced by the physical properties of the host sediment. Areas with a high rate of deposition of coarse clastic sediments may contain good fluid migration systems, which is beneficial for the formation of gas hydrate. Therefore, research on the characteristics of sedimentary systems, such as their distribution, depositional environments, sedimentary facies, rates of deposition and subsidence, sediment types, and
sedimentary discontinuities, are useful for analyzing the deposition and accumulation conditions of gas hydrates. The results of research based on analyses of sedimentary sequences in combination with information on the geological settings and the distribution characteristics of BSRs are discussed below.

### 4.3.1. Depositional facies

Previous research has shown that submarine gravity flows, particularly bathymetric flows and turbidite deposits, and slump fans in delta fronts as well as slope fans located in structural transition belts are favorable depositional systems or facies zones for the development and occurrence of gas hydrates (Yu et al., 2004). In sequence III, BSRs are mostly distributed in the bathyal facies of the Xisha and Shenhu districts, which indicates that the main controlling factors are temperature and pressure rather than depositional facies. In sequence II, BSRs occur widely in the Xisha, Shenhu, and Dongsha districts, mainly depositional systems that include deltas, turbidite fans and slope fans. In addition, there are some BSRs in neritic, bathyal, and contourite sediments, which shows that in medium burial depth strata, the formation of gas hydrates is obviously controlled by the depositional facies. In sequence I, BSRs are only present in the Qiongdongnan district, and almost all of them are located in the delta front and prodelta sediments. This suggests that in shallow burial depth strata, the most favorable sedimentary properties are required, and the control function of the depositional facies is more obvious. In brief, the more shallow the strata are, the more we interpret that BSR occurrence is controlled by the depositional facies, and a better relationship can be shown between BSR occurrence and a high rate of deposition of a depositional system, particularly for deltas (Fig. 9, Table 1).

### 4.3.2. Rate of deposition

The rate of deposition is an important factor controlling gas hydrate accumulation (Dillon et al., 1998; Gering, 2003). This is mainly because coarse-grained clastic sediments with a high rate of deposition can easily form an undercompacted area, which may constitute a good fluid migration system for promoting the formation of gas hydrates. The relationship between rate of deposition and BSR occurrence also varies greatly as the strata burial depth changes.

<table>
<thead>
<tr>
<th>BSR no.</th>
<th>Depositional facies</th>
<th>Deposition rate (cm/ka)</th>
<th>Sand content (%)</th>
<th>Heat flow (mw/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence II</td>
<td>1 Shallow sea</td>
<td>4–12</td>
<td>4–18</td>
<td>60–80</td>
</tr>
<tr>
<td></td>
<td>2 Delta</td>
<td>12–44</td>
<td>20–40</td>
<td>65–85</td>
</tr>
<tr>
<td></td>
<td>3 Turbidite</td>
<td>2–4</td>
<td>10–12</td>
<td>80–85</td>
</tr>
<tr>
<td></td>
<td>4 Deep sea</td>
<td>2–4</td>
<td>2–4</td>
<td>75–80</td>
</tr>
<tr>
<td></td>
<td>5 Turbidite</td>
<td>4–6</td>
<td>2–20</td>
<td>70–75</td>
</tr>
<tr>
<td></td>
<td>6 Debris flow</td>
<td>6–8</td>
<td>10–22</td>
<td>75–90</td>
</tr>
<tr>
<td></td>
<td>7 Deep sea</td>
<td>8–10</td>
<td>2–6</td>
<td>80–100</td>
</tr>
<tr>
<td></td>
<td>8 Delta</td>
<td>4–6</td>
<td>28–40</td>
<td>70–90</td>
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<tr>
<td></td>
<td>9 Contour current</td>
<td>2–10</td>
<td>12–24</td>
<td>75–100</td>
</tr>
<tr>
<td></td>
<td>10 Deep sea</td>
<td>4–6</td>
<td>6–10</td>
<td>70–80</td>
</tr>
<tr>
<td>Sequence III</td>
<td>11 Delta</td>
<td>4–6</td>
<td>26–32</td>
<td>60–70</td>
</tr>
<tr>
<td></td>
<td>12 Shallow sea</td>
<td>4–12</td>
<td>22–26</td>
<td>75–85</td>
</tr>
<tr>
<td></td>
<td>13 Bathyal sea</td>
<td>2–4</td>
<td>10–14</td>
<td>65–90</td>
</tr>
<tr>
<td></td>
<td>14 Bathyal sea</td>
<td>2–4</td>
<td>6–10</td>
<td>70–75</td>
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<tr>
<td></td>
<td>15 Slump</td>
<td>1–4</td>
<td>16–18</td>
<td>75–85</td>
</tr>
<tr>
<td></td>
<td>16 Slump</td>
<td>2–4</td>
<td>16–18</td>
<td>75–85</td>
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<tr>
<td></td>
<td>17 Shallow sea</td>
<td>4–6</td>
<td>16–20</td>
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<tr>
<td></td>
<td>18 Bathyal sea</td>
<td>2–4</td>
<td>10–20</td>
<td>90–100</td>
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<tr>
<td></td>
<td>19 Debris flow</td>
<td>2–4</td>
<td>8–12</td>
<td>80–95</td>
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<td></td>
<td>20 Deep sea</td>
<td>&lt;2</td>
<td>6–8</td>
<td>70–75</td>
</tr>
<tr>
<td>Sequence I</td>
<td>21 Delta</td>
<td>6–10</td>
<td>4–46</td>
<td>70–75</td>
</tr>
<tr>
<td></td>
<td>22 Shallow sea</td>
<td>8–20</td>
<td>8–24</td>
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<td>23 Delta</td>
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<td>36–46</td>
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<td></td>
<td>24 Delta</td>
<td>22–30</td>
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<td></td>
<td>25 Delta</td>
<td>16–18</td>
<td>40–48</td>
<td>80–85</td>
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<tr>
<td></td>
<td>26 Delta</td>
<td>12–18</td>
<td>24–48</td>
<td>75–85</td>
</tr>
</tbody>
</table>

Figure 10. Deposition rate of sequence II, BSRs are mainly distributed in the area with deposition rate about 4–30 cm/ka. The relationship between rate of deposition and BSR occurrence also varies greatly as the strata burial depth changes.
changes. Areas with a high rate of deposition generally have a better reservoir space and a stronger fluid conduction ability. Taking sequence II as an example, BSRs are mainly distributed in the area with a high depositional rate (Fig. 10, Table 1), which suggests a preference for a better reservoir space and conducting system. Generally, in the BSR distribution region, a deeper burial depth is always accompanied by a smaller rate of deposition and vice versa.

4.3.3. Sand content

The sand content directly influences the development of reservoir space and pore water, thus finally affecting the development of gas hydrates. In general, a smaller sand content will lead to less reservoir space, which is not conducive to the formation of gas hydrates. Conversely, a higher sand content will provide more reservoir space, which is favorable for gas hydrate formation. Many gas hydrate field expeditions have shown that the occurrence of gas hydrate is mostly controlled by the presence of coarser grained sediments in which gas hydrate are disseminated in the pores of sand-rich reservoirs (Collett et al., 2009). Because of the relatively distal nature of the deep-marine geologic settings, the overall abundance of sand within the shallow geologic section is commonly low (Collett et al., 2009). Taking sequence II as an example, in the southern part, BSRs are mainly distributed in areas with a low sand content ranges from 8% to 20%, whereas in the northern part, BSRs are mainly distributed in areas with a high sand content ranges from 20% to 40% (Fig. 9, Table 1). This may suggests that for strata with a medium burial depth, the reservoir space, which is not conducive to the formation of gas hydrates. In general, a smaller sand content will lead to less reservoir space and pore water, thus making it easy to capture a large amount of natural gases. In addition, clinoforms have an important influence on the distribution of gas hydrate (Wang et al., 2011b).

4.3.4. Lithological characters

It has been shown that sediment grain size does play an important role in controlling the saturation level of gas hydrate (Boswell et al., 2012a). At present, the gas hydrates that have been found in the SCS mainly occur in fine-grained sediments consisted of calcareous nannofossils silt and clayey silt, which have lenticular, nodular, granular or flaky shapes. Grain size analysis at the coring intervals in the Shenhu drilling area suggests that the sediments are homogeneous and fine-grained. The gas hydrate-bearing layers are mainly composed of clayey silt at site A and silt at site C. The lithological components of the gas hydrate-bearing layers are not significantly different from those of the layers present above and below (Table 2). Previous studies have shown that gas hydrate occurs within units of clayey silt and silt containing abundant calcareous nannofossils and foraminifer, which increase the porosities of the fine-grained sediments and provide space for enhanced gas hydrate formation (Wang et al., 2011b).

4.4. Special sedimentary structures related to the development of BSRs

4.4.1. Structural slope-break zone

The structural slope-break zone, where there is an abrupt change in the depositional slope, is initiated by the long-term activity of the syndepositional structure, which constrains the change in the accommodation space of the basin and controls the development of the depositional sequence, the distribution of the depositional system tracts and the sand bodies (Lin et al., 2000). Structural slope-break zones generally have a large terrain slope declination and sedimentary thickness. Additionally, these are near the main gas source area, and faults are relatively developed at their bases. The sediment grains are coarser in structural slope-break zones and the reservoirs are widely developed, which makes it easy to capture a large amount of natural gases. In addition, clinoforms have an important influence on the distribution of gas hydrate (Figs. 10, 11, Table 1).
deep-water gravity-flow depositional systems. Conversely, the gravity flow sedimentation process will also transform the slope morphology (Li et al., 2012). The northern continental marginal basins of the SCS underwent the periods of rifting and subsequent thermal subsidence. During rifting, a great number of faults were developed, and large-scale synegenetic faults often evolved at the edge of the depression. These faults bounded the basin and the ancient landforms. During subsequent activity, these faults also controlled the fluctuation and evolution of the continental slopes, and these areas are known as fault slope breaks. Favorable conditions for the enrichment of gas hydrates in these fault slope-break zones existed (Fig. 11). First, the fault slope breaks were connected with the lower hydrocarbon generation depression, which is a sufficient thermogenic gas source. Second, fault slope breaks are often developed on submarine fan turbidite sand bodies and slump deposit bodies, which can provide good reservoir conditions for the formation of gas hydrate. Third, the submarine topography in the slope-break zones is rugged. Subaqueous fan and submarine fan sand bodies formed along the slope breaks also can be good channels for the lateral migration of gas hydrates (Wu et al., 2008).

4.4.2. Slump blocks
Slump blocks are a type of sediment gravity flow, they are mass flows and high-density flows induced by direct or indirect paroxysmal factors. Since the late 1970s, gas hydrates have been reported to occur in submarine slumps, and slump blocks and BSRs have been observed on seismic profiles. Further research has shown a close relationship between submarine landslides and the decomposition and formation of gas hydrates (Brown et al., 2006). Tectonic movements or sea level declination can cause significant release of water and gas from gas hydrate dissociation, which increases the overlying fluid hydrostatic pressure. Under the direct effect of the gravity or induced by external factors (e.g., tsunamis, storms), the gas hydrate-bearing layers begin sliding or slumping along the continental slope. BSRs are usually present in contour current, turbidity current, and slump block depositional systems that have a rapid sedimentation rate. These depositional systems usually occur in areas with a high rate of deposition and a large thickness of sediments (Fig. 12). Therefore, they could become a favorable facies for gas hydrate accumulation.

4.4.3. Sediment waves
Deepwater sediment waves are one of the most distinct and frequently described submarine bedforms (Cartigny et al., 2011). They are distributed over a range of depths, from the shelf to the continental slope and rise and in abyssal plain environments (Wynn et al., 2000; Gong et al., 2012). Deep-water sediment waves are mainly generated by bottom currents (contour currents) or turbidity currents or by the interactions between down- and along-slope processes (Embley and Langseth, 1977; Gong et al., 2012).

Contourites are part of an important type of deep-water depositional system (Wold, 1994; Stow, 2002). Contourites have coarse grain size, good reservoir properties, a sufficient gas source, and excellent fluid migration conditions, and hence, they provide quite favorable settings for the formation of gas hydrates. Good contour current sedimentation areas are always gas hydrate-rich regions (Yang et al., 2002). Contourites are widely developed within the Pliocene and Quaternary strata at water depths ranging from 500 to 5000 m in the northern continental slope of the SCS (Wang et al., 2008b). There are obvious sheet waveform seismic facies in the eastern Dongsha area at water depths of 3100–3300 m, which are speculated to be the response of seismic facies to large contour current migration sediments (Fig. 11). The bottom of this sediment has an obvious detachment surface, resulting from the strong erosive ability of the contour current together with the effect of shaking and early sediment redeposition. The frequent erosion interfaces may reflect the pulsations of contour currents. These sediments are located in the favorable temperature and pressure interval for gas hydrate accumulation and have suitable physical properties; therefore, they can be considered as a suitable facies for gas hydrate accumulation (Yu and Zhang, 2005).

5. Model for deposition and accumulation of gas hydrate
A typical gas hydrate deposition and accumulation model for the northern continental slope of the SCS is summarized in Figure 13. Above the continental shelf, there are no BSRs because of the absence of suitable temperature and pressure conditions for gas hydrate formation and preservation. On the continental shelf, BSRs have a close relationship with the high deposition rate delta, and mainly occur in the delta front; thus, the lowstand systems tract (LST) formed by the lowstand normal regression (LNR) is more suitable for the occurrence of gas hydrate than that of the normal regression (NR) and highstand normal regression (HNR). The source is mainly deep thermogenic gas that vertically migrated through faults and gas chimneys. The key to gas hydrate formation and accumulation lies in the transportation and migration conditions. In the continental slope with an obvious

Figure 11. Typical seismic profiles in the northern continental slope of SCS. The location of each seismic profile is shown in Figure 3. AA’ and BB’: In the continental shelf, BSRs have close relationship with the high deposition rate delta; CC’ and DD’: In the continental slope with obvious topographic slope, BSRs mainly occur in the slump bodies and have close relationship with gas chimneys, they often show discontinuous distribution and topography caused by faults cutting; EE’ and FF’: In the continental rise and deep sea area, BSRs showed a close relationship with turbidity current and contour current.
topographic slope, BSRs mainly occur in slump bodies and often show discontinuous distribution and topography caused by fault cutting in the slope-break belt, the trough and the diapiric area. The source has a mixed origin, comprising deep thermogenic gas and shallow biogenic gas. In the continental rise and deep sea areas, BSRs are distributed in submarine fans, turbidity current and contour current deposits, and their lateral distribution is more continuous because of the smoother topography. This region lacks faults and gas chimneys linking to deep thermogenic gas; thus, the gas source is mainly from shallow biogenic gas and through lateral migration.

As a whole, BSRs show a close relationship with high deposition rate deltas, slope-break zones, deep-water gravity flows, and contourite sediments. Areas with rapid sediment unloading can provide favorable sedimentary reservoir conditions for gas hydrates, particularly gravity flows below the slope, including slide blocks, slump blocks, sandy clastic currents, and turbidity currents. A majority of the BSRs are located in zones with steep and rough relief with long-term successive uplift and subsidence on the seaward side. Since the depositional process was regression, it was favorable for the development of gravity-flow deposits in the slope zone, which can provide a suitable reservoir space for the formation of gas hydrates. In addition, a small number of BSRs occur in areas with relatively simple and flat topography with deeper water, weaker gravity flows, and more active bottom current flows. Though the overall trend of heat flow and geothermal gradient values increase in the seaward direction (Yuan et al., 2009; Zhang et al., 2011), the GHSZ predicted by the gas hydrate phase equilibrium curve shows initial thickening and then thinning as the water depth increases.

6. Conclusions

(1) 26 BSR distribution regions were identified in the northern continental slope of the SCS. The overwhelming majority of BSR distribution regions are located in areas with steep relief showing a significant variation in the terrain, and long-term successive subsidence. In addition, a small amount of BSRs is distributed in regions with relatively flat topography having a water depth greater than 2000 m. The grain size content of the gas hydrate-bearing sediments is mostly clayey silt and silt, with the silt content being about 70%.

(2) The northern SCS has appropriate temperature and pressure conditions and an adequate gas supply for the formation and occurrence of gas hydrates, but these are necessary rather
than sufficient conditions for the occurrence of gas hydrates. Once these conditions are satisfied, the occurrence of BSRs is more obviously controlled by depositional systems and geological structures. Widely developed faults and diapirc structures can be regarded as gas migration pathways. They are closely related to specific geological bodies such as structural slope-break zones and slump bodies. The heat flow range in the BSR area is within 65–90 Mw/m², and mainly between 75 and 85 Mw/m². The GHISZ shows initial thickening and then thinning with increasing water depth.

(3) Gas hydrates are often closely related to gravity flows, which mainly occur in contourites, several types of fans, and delta fronts. In the continental shelf, the key controls on gas hydrate accumulation are transportation and gas migration conditions. In the continental slope with an obvious topographic slope, BSRs mainly occur in slump bodies and often show discontinuous distribution and topography caused by fault cutting at the slope-break belt, the trough, and the diapirc area. In the continental rise and the deep sea, BSRs are distributed in submarine fan, turbidity current, and contour current sediments, and their lateral distribution is more continuous.

Acknowledgments

This work was supported by the National Key Basic Research Program (Grant No. 2009CB219502), the National 127 Project (Grant No. GH2010010105) and the National Science and Technology Major Project of China (Grant No. 2011ZX05023-001-009). We are grateful to the China Geological Survey Bureau, Guangzhou Marine Geological Survey. We would also like to thank all the students in our workgroup, and all the people who provided us with invaluable help. We also thank the reviewers for their constructive comments and suggestions, which improved the manuscript.

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