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Focused fluid flow in the Baiyun Sag, northern South China Sea: implications for the source of gas in hydrate reservoirs*

CHEN Duanxin (陈端新)[1, 2], WU Shiguo (吴时国)[1, **], DONG Dongdong (董冬冬)[1], MI Lijun (米立军)[3], FU Shaoying (付少英)[4], SHI Hesheng (施和生)[5]

[1] *Key Laboratory of Marine Geology & Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China*

[2] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

[3] *Exploration Department, China National Offshore Oil Corporation (CNOOC), Beijing 100010, China*

[4] *Guangzhou Marine Geology Survey, Guangzhou 510760, China*

[5] *Shenzhen Branch of CNOOC, Shenzhen 518067, China*

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Abstract The origin and migration of natural gas and the accumulation of gas hydrates within the Pearl River Mouth Basin of the northern South China Sea are poorly understood. Based on high-resolution 2D/3D seismic data, three environments of focused fluid flow: gas chimneys, mud diapirs and active faults have been identified. Widespread gas chimneys that act as important conduits for fluid flow are located below bottom simulating reflections and above basal uplifts. The occurrence and evolution of gas chimneys can be divided into a violent eruptive stage and a quiet seepage stage. For most gas chimneys, the strong eruptions are deduced to have happened during the Dongsha Movement in the latest Miocene, which are observed below Pliocene strata and few active faults develop above the top of the Miocene. The formation pressures of the Baiyun Sag currently are considered to be normal, based on these terms: 1) Borehole pressure tests with pressure coefficients of 1.043–1.047; 2) The distribution of gas chimneys is limited to strata older than the Pliocene; 3) Disseminated methane hydrates, rather than fractured hydrates, are found in the hydrate samples; 4) The gas hydrate is mainly charged with biogenic gas rather than thermogenic gas based on the chemical tests from gas hydrates cores. However, periods of quiet focused fluid flow also enable the establishment of good conduits for the migration of abundant biogenic gas and lesser volumes of thermogenic gas. A geological model governing fluid flow has been proposed to interpret the release of overpressure, the migration of fluids and the formation of gas hydrates, in an integrated manner. This model suggests that gas chimneys positioned above basal uplifts were caused by the Dongsha Movement at about 5.5 Ma. Biogenic gas occupies the strata above the base of the middle Miocene and migrates slowly into the gas chimney columns. Some of the biogenic gas and small volumes of thermogenic gas eventually contribute to the formation of the gas hydrates.

Keyword: gas hydrate; thermogenic gas; biogenic gas; Dongsha Movement; focused fluid flow; South China Sea

1 INTRODUCTION

Focused fluid flow systems, which are usually caused by strata overpressure and serve as important conduits for the formation of gas hydrates, are common in deepwater basins (Hovland et al., 1997; Judd et al., 2002; Gay et al., 2006; Judd and Hovland, 2007). These systems are also described in the Baiyun Sag in the Pearl River Mouth Basin, northern South China Sea (Sun et al., 2012a). However, processes related to the release of overpressure, thermogenic fluid flow and the formation of gas hydrates, have previously been poorly understood. Gas chimneys

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** Corresponding author: swu@qdio.ac.cn

underlying bottom simulating reflections (BSRs) in seismic data show that thermogenic fluids can migrate into the gas hydrate stability zone (Wu et al., 2005, 2010; He et al., 2011; Su et al., 2011; Sun et al., 2012b). The $\delta^{13}C_1$ values of acid-degassed gases (i.e., gas adsorbed to mineral grains within the sedimentary samples) acquired from hydrate layers vary from -29.8 to -48.2, which indicates that thermogenic gas ever migrated to shallow sediments (Huang et al., 2010). However, the results of chemical tests suggest that methane extracted from hydrate samples and associated headspace (i.e., free gas and the gas dissolved in fluid) are mainly biogenic in origin with a methane content of more than 99%, ratios of $C_1/(C_2+C_3)$ close to or higher than 1 000 and methane $\delta^{13}C_1$ values ranging from -54.1 to -62.2 (Kvenvolden et al., 1993; Kvenvolden, 1995; Yang et al., 2008; Pohlmann et al., 2009; Huang et al., 2010; Wang et al., 2011). The cause of the release of overpressure, the method by which the thermogenic fluid migrated, and the formation of gas hydrate are also poorly understood.

In this study, chemical test results (Huang et al., 2010), lithology timing results and wire-line logging curves of the hydrate cores will be applied in an integrated manner. Using high-resolution seismic data, well data from conventional petroleum and gas hydrate wells drilled in the continental slope, together with a consideration of the local tectonic and sedimentary evolution, this study will focus on: (1) imaging focused fluid flow in the Baiyun Sag, (2) understanding the dynamic process of focused fluid flow associated with gas migration and gas hydrate formation, and (3) proposing a possible triggering mechanism for the release of overpressured fluid. Finally, a geological model concerning the tectonic event, the processes of fluid flow and the formation of gas hydrates is proposed.

2 GEOLOGICAL SETTING

The northern South China Sea is a typical passive continental margin with a depositional history commencing in the Cenozoic (Taylor and Hayes, 1982). The tectonic evolution of Pearl River Mouth Basin (Fig.1) is divided at about 23.8 Ma into a Paleogene syn-rift stage and a Neogene and Quaternary post-rift stage (Clift et al., 2002; Zhu et al., 2007; Dong et al., 2009). Post-rift subsidence and sedimentation anomalies in the Baiyun Sag were intensely influenced by thermal subsidence. However, an extensive tectonic event also seriously influenced the partial strata in the basin. The Dongsha Movement began in the latest Miocene due to the collision of the northwestward-moving Philippine Sea Plate with the Eurasian Plate, resulting in the development of a large number of NW-NWW oriented strike-slip faults and the instigation of magmatic activities in the eastern Pearl River Mouth Basin. Subaerial exposures and intense erosion also occurred. Post-Miocene, the movement became weaker and dissipated (Li and Rao, 1994; Yao, 1999; Zhao et al., 2012). Two collisional phases have been inferred by others (Lüdmann et al., 1999; Lüdmann and Wong 2001); however, our research on the Dongsha Rise supports a single collision in the latest Miocene (Zhao et al., 2012).

The sequences in this area can also be divided into a syn-rift stage before 23.8 Ma and post-rift stage after 23.8 Ma (Zhu et al., 2007; Dong et al., 2009). The sedimentary facies (Fig.2) in the syn-rift stage vary from lacustrine facies (Wenchang Formation, 49–36 Ma) to swamp facies (Enping Formation, 36–30 Ma) and shoreface facies (Zhuhai Formation, 30–23.8 Ma) (Xie et al., 2006). The facies from the post-rift stage are dominated by bathyal and abyssal facies (Xie et al., 2006). Total Organic Carbon (TOC) in the Enping, Zhuhai and Zhujiang formations amounts to 2.19%, 1.0%–1.5% and less than 0.6%, respectively, in LW3-1-1, a deep well drilled near the gas hydrate wells in this study area (Zhu et al., 2008). The total thickness of sediments in the Baiyun Sag exceeds 11 000 m with a considerable thickness of source rocks (>6 000 m) occurring at the center of the depositional region (Zhu et al., 2008).

The gas hydrates discussed in this study, are disseminated within the pore spaces of fine-grained clay sediments (Zhang et al., 2007) (Fig.2). The complicated lithologies and structural patterns caused by bottom currents and turbidity currents complicate the seismic facies of the shallow sediments (Zhu et al. 2010). Gas hydrates were obtained from the upper Miocene or Pliocene on canyon ridges consisting of clay minerals, carbonate minerals and detrital matter (Lu et al., 2009).

3 DATA AND METHOD

Integrated analysis of 2D and 3D seismic data, together with geochemical analyses of samples collected in gas hydrate wells and adjacent conventional oil wells, were used to study focused fluid flow and its influence on gas hydrate formation. The 3D seismic dataset acquired by the China

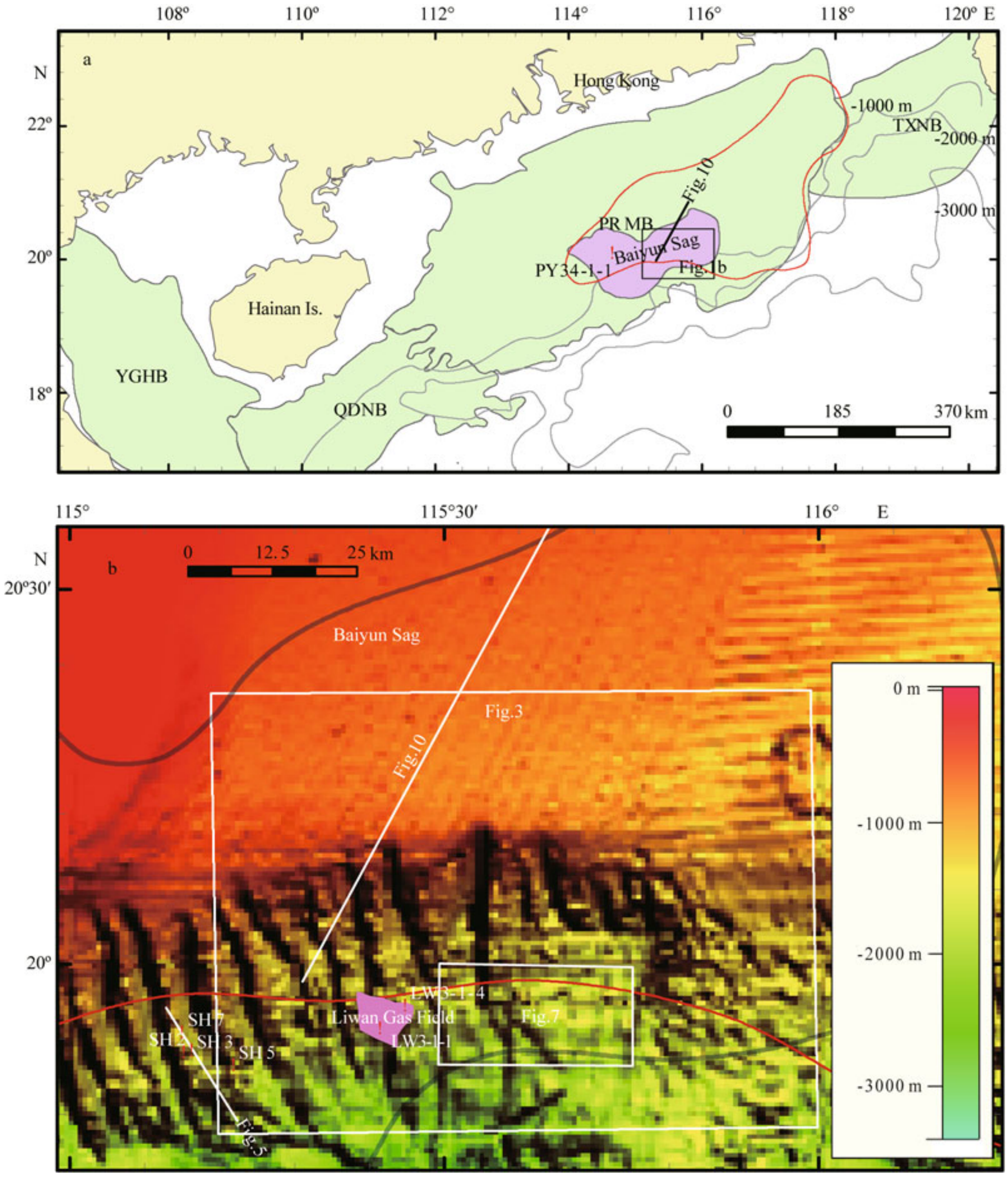

Fig.1 a. Sedimentary basins on the northern South China Sea margin. TXNB-Taixinan Basin, PRMB-Pearl River Mouth Basin, QDNB-Qiongdongnan Basin, YGHB-Yinggehai Basin. The pink color indicates the Baiyun Sag within the PRMB. The zone inside the red line represents areas influenced by the Dongsha Movement (Modified from Zhao et al., 2012). The rectangle represents the three dimensional (3D) survey. Industrial gas well PY34-1-1, which has the same gas source as the Liwan gas field, is used to compare with the gas hydrate wells. b. Geomorphology of gas hydrate drilling sites. Figure locations as shown. The heavy line represents the edge of the Baiyun Sag. The rectangle presents the 3D survey. The red line has the same meaning as in Fig.1a. Industrial gas wells LW3-1-1 and LW3-1-4 drilled in the Liwan gas field are labeled in pink

National Offshore Oil Corporation covers approximately 4 300 km^2 in water depths of 500–1 800 m. The acquisition used a tuned array of 8×20 inch^3 air guns and 3 000-m-long streamers with a hydrophone group interval of 12.5 m. The sampling interval was 4 ms and the bin spacing was 25 m (in the crossline direction)×12.5 m (in the inline direction). The dominant frequency is dependent on depth, approximately 40 Hz for the shallowest 1 500 m. Seismic interpretations describe gas chimneys, mud diapirs, and active faults. Because of the small fault throw and limited fault length,

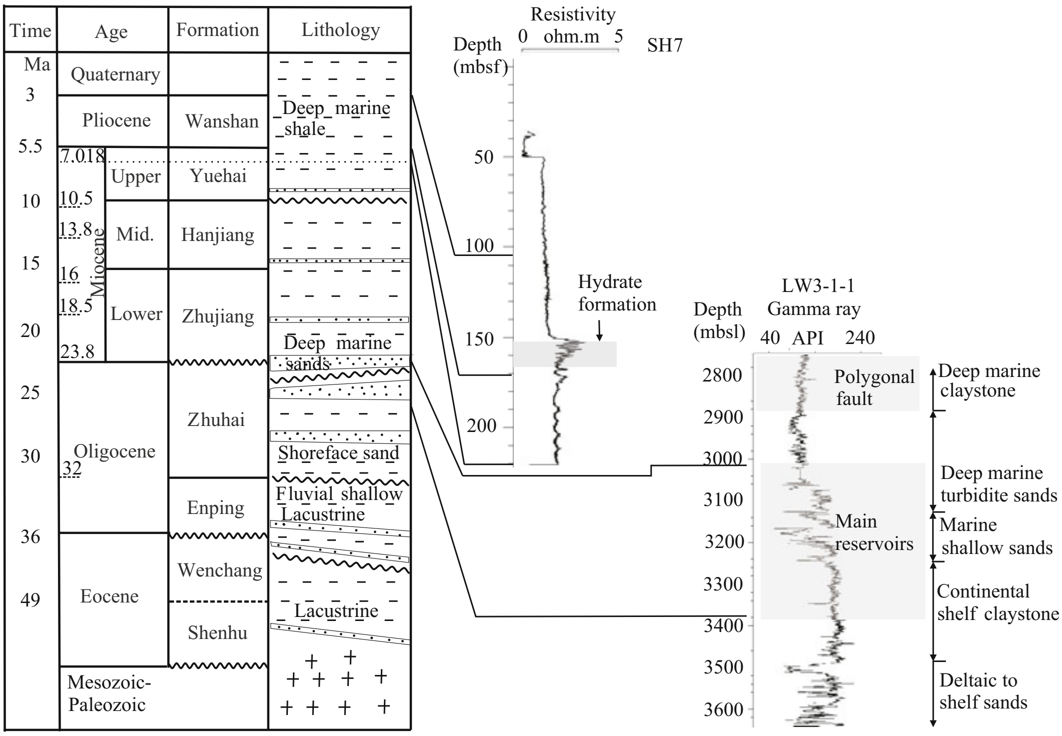

Fig.2 Stratigraphy of the Baiyun Sag (modified from Xie et al., 2006)

The resistivity log curve is shown for the hydrate section in well SH7, and the gamma ray log curve of industrial gas well LW3-1-1 is also shown. The intervals where gas hydrates, polygonal faults and main reservoirs developed are labeled in the log column.

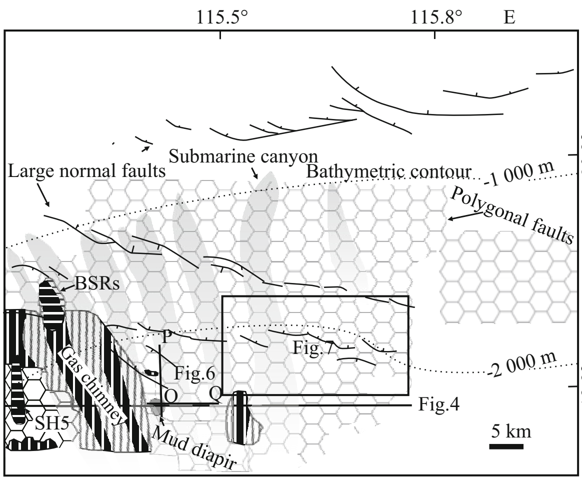

Fig.3 Distribution of focused fluid flow features, BSRs and submarine canyons in the 3D survey

See Fig.1b for location. Parallel N-S lines represent the distribution of gas chimneys. Parallel E-W lines represent the distribution of BSRs. The dark circle marks a mud diapir. The extent of polygonal faults is indicated by the hexagonal pattern. Dark bands indicate the locations of submarine canyons. Arcuate lines represent deep-seated large normal faults. The seismic profile of POQ is displayed in Fig.6. Bathymetric contours at 1 000 and 2 000 m are shown.

polygonal faults in the study area are mainly described using high-resolution 3D seismic data and coherence slices are used to delineate the horizontal extent of polygonal faults. Formation pressures in the reservoirs were measured using the Modular Formation Dynamics Tester tool (MDT), recently developed by Schlumberger, which aimed to deliver real-time formation pressure information for the main reservoir (Anderson et al., 2011). The tests were conducted on the main reservoir intervals from 3 151 to 3 368.5 m (Fig.2). The formation pressure coefficient, calculated from the ratio of formation pressure to hydrostatic pressure, was selected to predict overpressure.

4 FOCUSED FLUID FLOW

Based on 2D and 3D seismic imaging, three types of focused fluid flow structures: gas chimneys, mud diapirs and active faults, have been found widely distributed in the Baiyun Sag (Figs.3–5). In each case, focused fluid could migrate from deep to shallow sediments. They are discussed separately below.

4.1 Gas chimneys

Gas chimneys are the most important migration pathways related to gas hydrate reservoirs in the Baiyun Sag (Wu et al., 2010; Sun et al., 2012a). The gas chimneys in this region usually have a diameter of about 2 km and penetrate through several kilometers

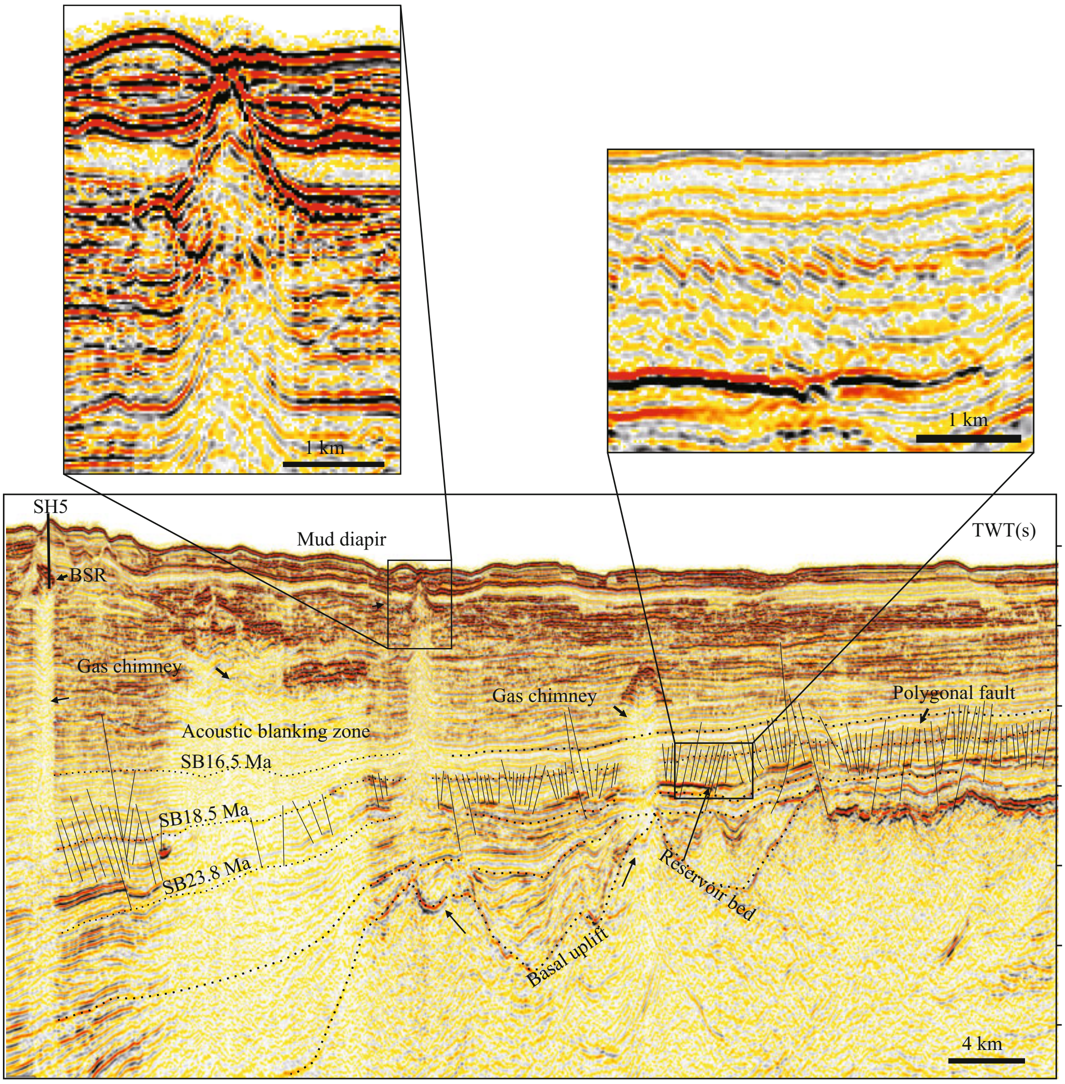

Fig.4 A seismic section showing gas chimneys, a mud diapir, and polygonal faults

See Fig.3 for locations. The sequence boundaries labeled SB16.5, SB18.5 and SB23.5 were calibrated by well LW3-1-1. Polygonal faults with small fault throws developed around SB18.5 and some large faults have penetrated into the gas reservoirs. The gas chimneys developed above basement uplifts. Note that the tops of the gas chimneys are a significant distance beneath the seafloor whether or not BSRs have developed. The enlarged sections above display the inner details of the mud diapir and polygonal faults.

of strata. A few are as much as 10 km wide. The gas chimneys usually have high-amplitude reflections at their tops and a blanking zone within them (Figs.4, 5), which makes their internal structures difficult to characterize. However, micro faults (tens of meters in seismic profiles) can be found inside some gas chimneys and in the high amplitude zones, which indicates that the micro faults may be more widespread within the blanking zones (Fig.5). Nearly all the gas chimneys are columnar, and ambiguous seismic reflections within the conduits show they result in a seismic "pull-down" caused by low velocities. We also observe small forced anticline-like structures around and at the top of gas chimneys. The gas chimneys usually are rooted in Paleogene gas reservoirs in the deep depression (Fig.4) and terminate at an upper Miocene surface beneath the BSRs (Figs.4 and 5).

4.2 Mud diapirs

A number of mud diapirs have been identified in the Baiyun Sag. The significant difference between focused fluid flow in gas chimneys and mud diapirs, is that the sedimentary sequences inside a gas chimney usually are not disturbed by the eruption of fluid, whereas upwelling mud always destroy the sequences inside a mud diapir (Fig.4). As a result, only chaotic reflections are imaged inside a mud diapir. The mud

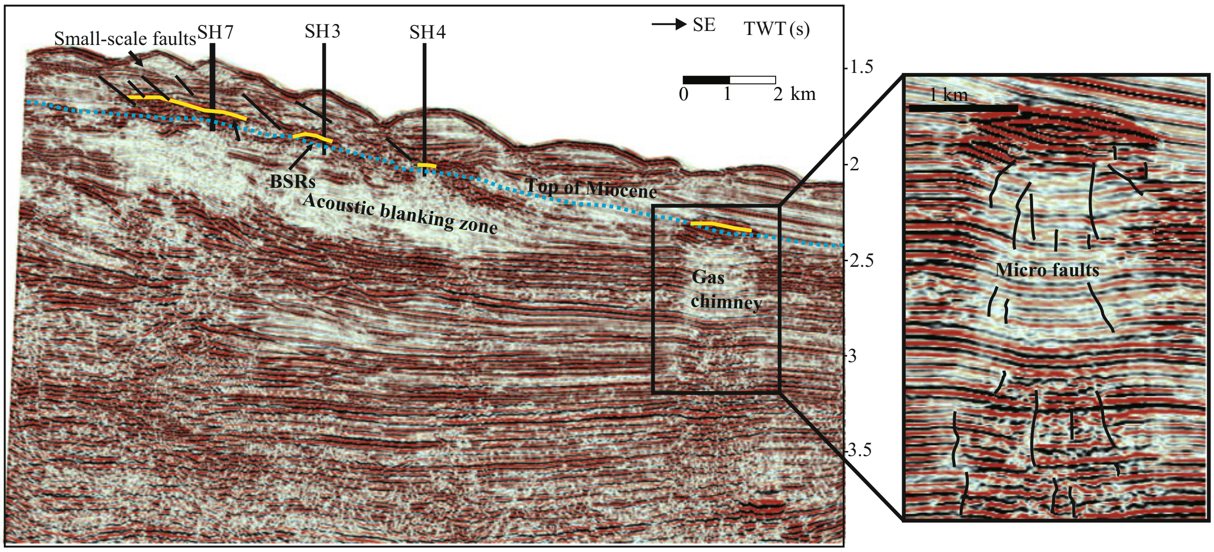

Fig.5 A seismic profile across gas hydrate wells SH3, SH4 and SH7

Acoustic blanking zones and gas chimneys occur beneath the BSRs. Micro faults are found in the interior of gas chimneys and small-scale faults lie above the BSRs. See Fig.1b for locations. The tops of the gas chimneys develop below the top of Miocene. The enlargement to the right shows the details of micro faults inside the gas chimney.

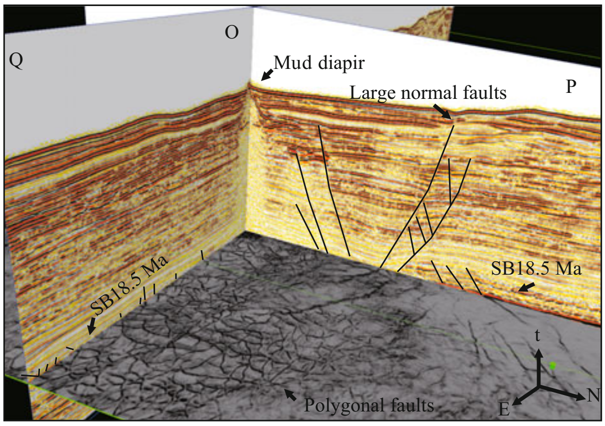

Fig.6 3D perspective of a mud diapir in the Baiyun Sag

The time coherence slice cuts across the polygonal faults. The large normal faults are located to the northeast of the gas hydrate reservoirs. See Fig.1b for locations.

diapirs in the Baiyun Sag are usually rooted in Eocene-early Oligocene source rocks and possess a tapered shape with the diameter of about 2 km and height of several kilometers. The sediments surrounding and overlying a mud diapir are forced into an anticline, indicating intrusion of material (mud) during formation (Figs.4 and 6). We cannot observe onlapping reflections at the top of the mud diapirs, which indicates that they did not become exposed on the paleo-seabed. Layering within the mud diapir is suggestive of multiphase upwellings, and a short distance between the seafloor and the top of the diapir gives an indication of how recent the last eruption was (Fig.4). The mud diapir featured here is also observed to have originated above the basement uplifts.

4.3 Active faults

Active normal faults, including large deep-seated faults, small-scale faults above BSRs, micro faults inside gas chimneys, and polygonal faults, are found in the study area. Large deep-seated faults extend vertically over several kilometers and laterally are zonally distributed (Figs.3 and 6). However, in the Baiyun Sag, they are generally positioned a long way from the gas hydrate zone. Small-scale faults overlying the BSRs are common and facilitate the migration of shallow gas to the seabed. Abundant micro faults developing inside gas chimneys are likely caused by eruptions of overpressured fluid that link deep gas sources to shallow sediments.

Polygonal faults are a network of layer-bounded, meso-scale extensional faults arranged in polygonal structures that develop in deepwater sequences (Cartwright, 1994a). They have been found to be common in deepwater basins all over the world and usually start to develop at shallow burial depths (Cartwright, 1994a; Cartwright and Lonergan, 1996; Watterson et al, 2000). In the Baiyun Sag, polygonal faults cover an area of 2 500 km^2 with lengths of 100–1 400 m, separations of 200–800 m and throws of 10–30 m. On average, the faults are observed to have developed in the central sequences at SB18.5 where

Table 1 Gas parameters collected from gas hydrate wells and adjacent conventional gas wells in the study area

Core No.	WD (m)	Depth in core (m)	CH_4%	C_2H_6%	C_3H_8%	*R*	$\delta^{13}C_1$	δD_{CH4}	Sequence	References
SH1B^{+}	1 261	-	76.48–94.69	-	-	5.0–22.7		-	-	Huang et al., 2010
SH2B^{+}	1 230	-	75.00–93.93	-	-	4.7–20.9	-29.8	-	-	Huang et al., 2010
SH5C^{+}	1 423	-	78.27–94.95	-	-	5.8–24.4	-48.2	-	-	Huang et al., 2010
SH7B^{+}	1 113	-	78.42–94.15	-	-	5.9–22.2		-	-	Huang et al., 2010
SH2B-12R*	1 230	197.50–197.95	99·89	0·09	0·01	911·7	-56.7	-199	YH Fm	Huang et al., 2010
SH3B-7P*	1 245	123.00–123.85	99·92	0·05	0·02	1 373.5	-62.2	-225	-	Huang et al., 2010
SH3B-13P$^{\&}$	1 245	190.50–191.35	99·91	0·08	0·01	1094	-60.9	-191	-	Huang et al., 2010
SH5C-11R*	1 423	114.00–114.93	99·96	0·04	0	2447	-54.1	-180	-	Huang et al., 2010
SH7B-11R	1 113	155.11–176..27	-	-	-	-	-	-	WS Fm.	Huang et al., 2008
LW3-1-1$^{\#}$	1 480	3 070	-	-	-	-	-37.1	-158.1	ZJ Fm.	Zhu et al., 2008
		3 144.5	-	-	-	-	-36.6	-158.4	ZH Fm.	Zhu et al., 2008
		3 189.5	-	-	-	-	-36.8	-155.8	ZH Fm.	Zhu et al., 2008
		3 499.5	-	-	-		-36.6	-175.6	ZH Fm.	Zhu et al., 2008
LW3-1-4$^{\#}$	1 332.6	-	-	-	-	-	-	-	-	
PY34-1-1$^{\#}$	192	480 - 510	98.60	0.01	-	-	-68.2	-	Q Fm.	Cui et al., 2009
		2 100–2 130	99.2	0.01	-	-	-59.7	-	HJ Fm.	Cui et al., 2009
		3 612–3 633	9.36	3.7	-	-	-34.6	-	ZJ Fm.	Cui et al., 2009
		3 650–3 660	78.8	4.14	-	-	-36.8	-	ZJ Fm.	Cui et al., 2009
		3 820–3 838	33.1	1.25	-	-	-35.3	-	ZJ Fm.	Cui et al., 2009

$R=C_1/(C_2+C_3)$; &: gases dissolved from gas hydrates; *: headspace gas test; #: industrial well; +: acid-degassed gases; -: no data.

they lie directly over the main reservoir horizon. They die out eastwards at the Dongsha Massif and northwards to the continental shelf break (Figs.3, 4, and 7).

5 DISCUSSION

5.1 Dynamic process of focused fluid flow

Previous studies proposed that the Baiyun Sag constitutes an overpressured environment (Chen et al., 2006; Shi et al., 2006). Tectonic subsidence, increasing relative sea level, a high sedimentation rate and abundant organic matter have all led to the formation of strata overpressure in deep Cenozoic mudstones and reservoir rocks (Pang et al., 2008; Zhu et al., 2007, 2009; Su et al., 2011). Tectonic subsidence in the center of the Baiyun Sag during the Cenozoic was up to 10 km (Dong et al., 2009) and the total thickness of sediments in the Baiyun Sag exceeds 11 km (Zhu et al., 2008). The high sedimentation rates reached 200 m/Ma during the deposition of the Wenchang (49–36 Ma) and Zhujiang and Hanjiang (23–10.5 Ma) formations (Dong et al., 2009). Most of the gas is sourced from the Enping Formation with an average TOC content of 2.19% (Zhu et al., 2008). The occurrence of widespread focused fluid flow, such as that seen in gas chimneys in the Baiyun Sag, support the existence of past overpressure regimes.

The strong focused fluid flow is inferred to connect with gas reservoirs based on seismic analysis (Fig.4). Assuming that these structures are filled with thermogenic fluid, the fluid could migrate to shallow sediments and leave chemical traces of its passing. The high carbon isotope and high volumetric ratio, $R=C_1/(C_2+C_3)$, of the acid degassed gas, are similar to the values in deep strata of LW3-1-1 and PY3-1-4 (Table 1). This might indicate that thermogenic gas had penetrated into the Yuehai and Wanshan formations during or after their deposition.

However, present-day focused fluid flow in this region is considered to be less active and the flux of thermogenic fluid flow is lower. Real-time strata pressure tests using the Modular Formation Dynamics Tester tool in the Liwan gas field show slightly high formation pressures, with pressure coefficients of 1.043–1.047 in the main reservoir intervals. Such values are usually considered to be representative of normal formation pressures (Fig.8). What's more, the

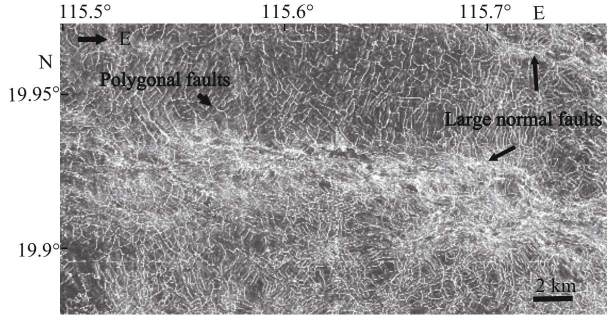

Fig.7 A flattened seismic coherence slice through sequence boundary SB 18.5 Ma highlights the planar characteristics of polygonal faults

A series of deep-seated large normal faults in the center has destroyed the otherwise regular image of polygonal faults. See Figs.1b and 3 for location.

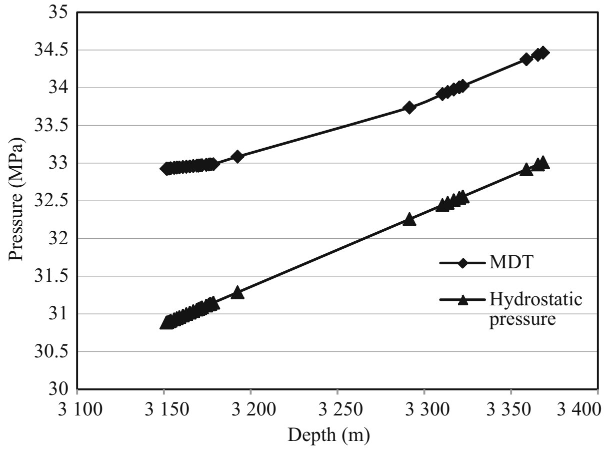

Fig.8 Formation pressure and hydrostatic pressure in the main reservoir intervals of LW3-1-4 next to LW3-1-1 from 3 151 to 3 368.5 m

Formation pressure data were obtained from the Modular Formation Dynamics Tester tool. The result shows the formation pressure in the reservoir is slightly higher than hydrostatic pressure with pressure coefficients of 1.043–1.047.

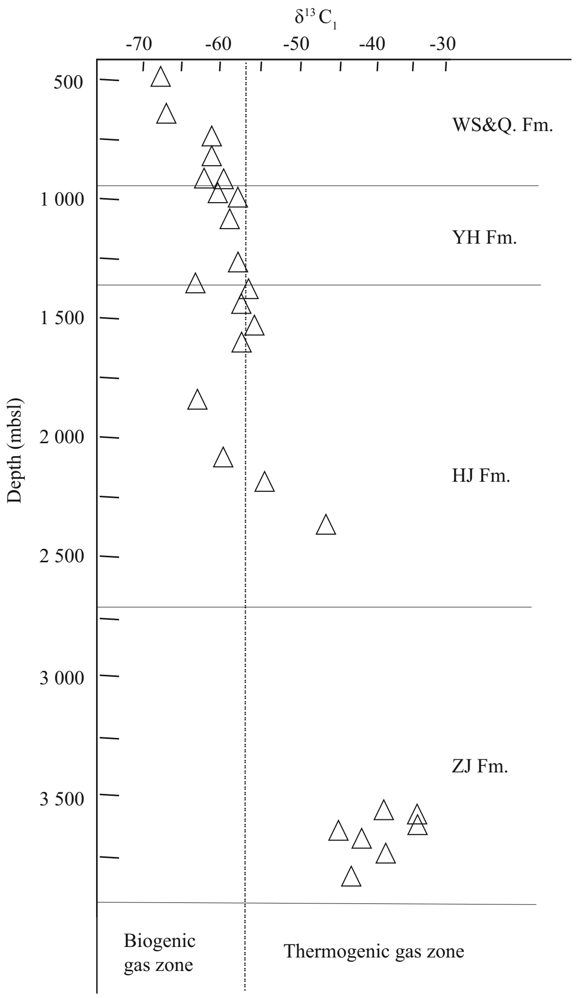

Fig.9 Carbon isotope values of methane in well PY34-1-1 from variable depths

Modified from Hou et al. (2008). The criterion for differentiating between biogenic and thermogenic gas using the carbon isotope of methane is 57, according to Kvenvolden (1995).

development of disseminated methane hydrates rather than fractured hydrates in the sediment samples significantly indicates a decreased flux of thermogenic fluid (Yang et al., 2008; Wu et al., 2009). In addition, carbon isotope values in the hydrate samples range from -54.1 to -62.2, in accordance with values varying from -55 to -65 in the Yuehai and Wanshan Formation of PY34-1-1 (Fig.9). This suggests that the gas in gas hydrate is mainly biogenic in origin. Unfortunately, in this process, very little or no CO_2 makes it difficult to identify whether or not there is a possibility of identifying isotope fractions (Huang et al., 2010).

Based on the evidence discussed above, fluid flow is interpreted to be subdued at present. In addition, gas hydrates are inferred to have eventually formed from accumulations of biogenic gas and small volumes of thermogenic gas, based on the variability of geochemical parameters of headspace gas and dissolved gas. Methane $\delta^{13}C_1$ values range from -54.1 to -62.2 and acid-degassed gas $\delta^{13}C_1$ values vary from -29.8 to -48.2 (Huang et al., 2010).

Polygonal faults have been demonstrated to serve as pathways for fluid flow (Berndt et al., 2003; Gay et al., 2006; Hustoft et al., 2007; Cullen et al., 2008; Sun et al., 2009, 2010). In addition to the gas chimneys and mud diapirs observed in the Baiyun Sag, deepwater polygonal faults are considered to be important for the focused fluid flow of thermogenic gas. The development of polygonal faults is usually limited to specific deepwater intervals of claystone as

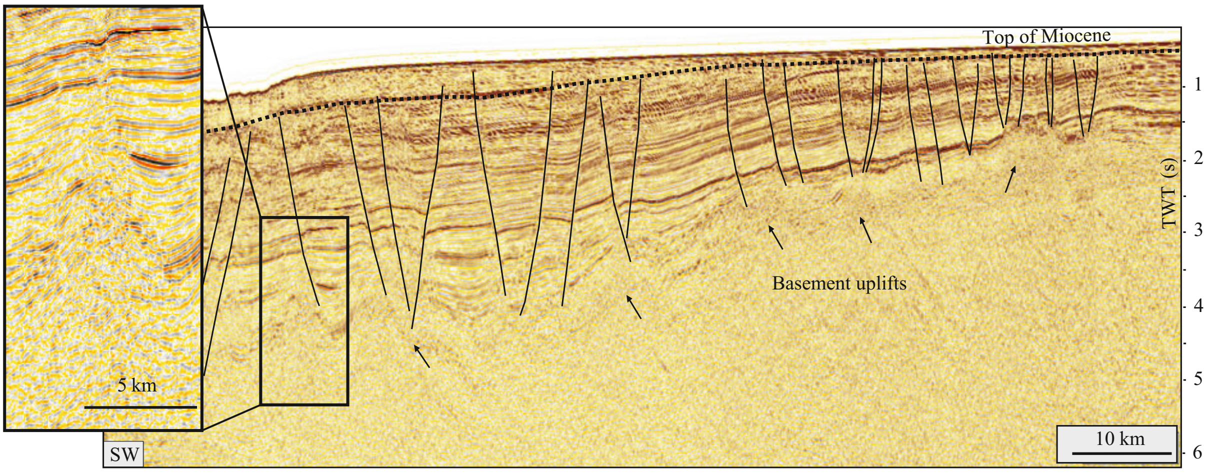

Fig.10 A seismic profile showing basement uplifts and NW oriented normal faults caused by the Dongsha Movement

Most of the NW oriented normal faults developed below the top of Miocene. See Fig.1b for location.

a result of hydrofracturing (Cartwright, 1994b). In this study, polygonal faults develop over deep marine turbidity sands, which are the main reservoirs in the Liwan gas field. When hydrofracturing occurred, deeply developed faults could pierce through the reservoir and thereby release overpressured fluid, particularly thermogenic gas, from the reservoir (Fig.4).

5.2 A possible trigger mechanism for the release of overpressured fluid

As discussed above, normal pressure, the type of porosity infilling, the origin of biogenic gas, and particularly the observation of a >200 m separation between the upper termination of gas chimneys and the seafloor, all support the conclusion that focused fluid flow events have not been occurring in the last few thousand years. For such an event to occur, conditions must change such that the pore pressure exceeds the yield pressure of the overlying strata. Failure could then occur and fluid would erupt. Fluid released by pore overpressure alone does not fit the observations in Baiyun Sag of so many gas chimneys with similar characteristics. Triggering of events by tectonic activities, slides, rapid sea level changes or earthquakes is likely to be needed. We consider tectonic movements to be most likely to trigger the release of strata overpressure. Observed gas chimneys, rooted over basement uplifts, support this point (Figs.4 and 10). Basement uplifts could misbalance the overpressure environment in the reservoir or source rock through both uplifting and faulting.

The Dongsha Movement involved extensive faulting, large-scale uplift and erosions, and the subsequent development of unconformities in the Pearl River Mouth Basin (Lüdmann et al., 1999; Zhao et al., 2012). This tectonic event happened during the latest Miocene based on the dating of unconformities and sequence stratigraphic evidences (Zhao et al., 2012). The effects of this event can be seen in seismic data across the Dongsha Massif and Baiyun Sag that display NWW oriented faults and unconformities (Fig.10). Most of the gas chimneys in this region are rooted above deeply faulted uplifts and usually terminate at or below the top of Miocene strata. As discussed above, a significant release of overpressure occurred during the Dongsha Movement, which induced the development of focused fluid flow below Pliocene strata. The movement then became weaker and disappeared after the Miocene.

The development of a framework for explaining seismic images of fluid flow is a priority. We think that gas chimneys can survive during periods of low flow. Normally, micro faults in gas chimneys serve as conduits for gas migration. As shown in well PY34-1-1 (Fig.9), abundant biogenic gas exists in and above the upper Hanjiang Formation (aged 13.8 Ma), more than 2 000 m below the seafloor. Even if mixed with small quantities of thermogenic gas, substantial amounts of biogenic gas could migrate up into paleo-gas chimneys and control the intense seismic signatures of the chimneys. Such gas could also make a significant contribution to the formation of highly concentrated methane hydrates (Zhu et al., 2008).

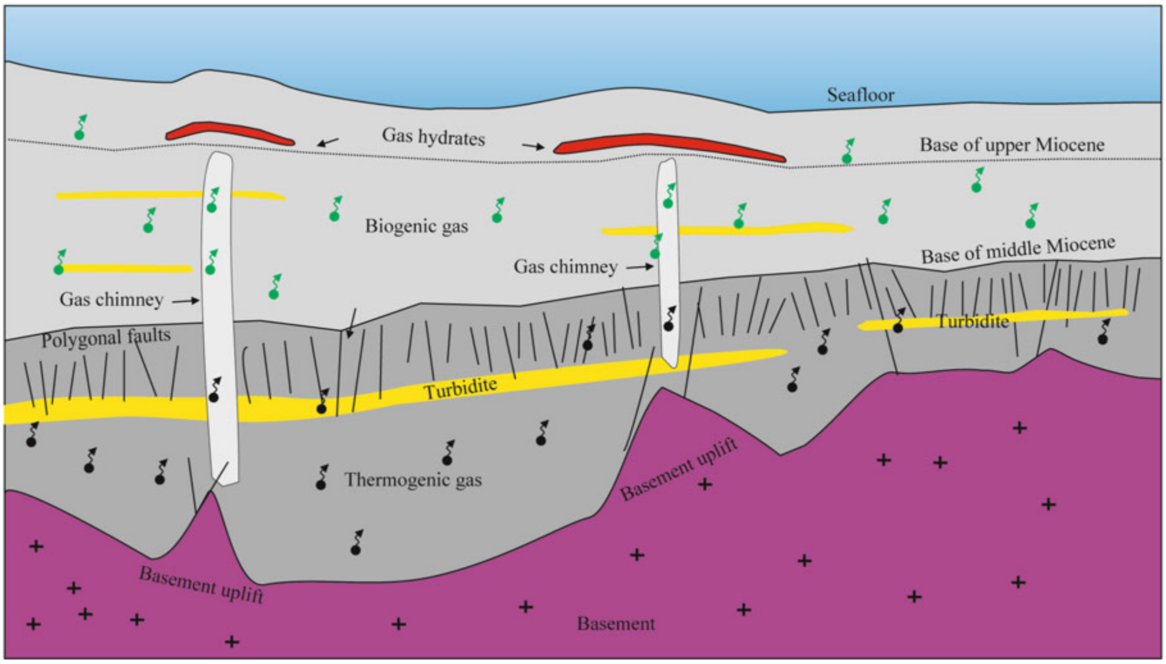

Fig.11 Geological model of fluid migration and the formation of gas hydrates

The Dongsha Movement caused basement uplifts and led to the release of overpressured fluid in reservoirs and the formation of gas chimneys. In the subsequent quiescent stage, micro faults in the gas chimneys still allowed the migration of some thermogenic gas combined with abundant shallow biogenic gas upward to form gas hydrates.

5.3 Geological model for overpressure fluid flow and formation of gas hydrate

A geological model has been proposed to explain the dynamic processes associated with the release of overpressure leading to the formation of focused fluid flow, fluid migration, and the formation of gas hydrate in Baiyun Sag (Fig.11). During the post-rift stage in the Baiyun Sag, tectonic subsidence, relative sea level change, a high sedimentation rate, and the supply of abundant organic matter to the Pearl River Mouth Basin led to a huge accumulation of sediment. As a result, formation overpressure formed in mudstone or sand reservoirs in the deep depression. In the latest Miocene, the Dongsha Movement caused the development of extensive basement uplifts and NW-oriented faults. This induced the release of overpressured fluid in deep strata. Vigorous eruptions through the basin produced large-scale gas eruption structures such as gas chimneys, which facilitated the migration and high flux of thermogenic gas from deep layers to shallow sediments. This gas diffused in the shallow sediments where some of it was enclosed in fluid inclusions. After the Miocene, tectonic movements became weaker. In addition to decreasing pressure, fluid pathways became inactive and the flux of thermogenic fluids dropped. Biogenetic gas produced from rich organic matter in the shallow strata mixed with small amounts of thermogenic gas filled the gas chimneys to form the gas hydrates that have now been sampled in the study area.

6 CONCLUSION

Three types of focused fluid flow systems: gas chimneys, mud diapirs and active faults are imaged in 2D and 3D seismic data from the Baiyun Sag. Gas chimneys underlying BSRs have been identified as the most important pathways for fluid migration. This migration of gas was induced by the release of overpressured fluid, which was most likely caused by the tectonic events of the latest Miocene aged Dongsha Movement. During the subsequent quiescent stage of focused fluid flow, gas chimneys become inactive and the flux of thermogenic fluids decreased. However, the pathways still acted as conduits for gas migration. Abundant biogenic gas in the shallow sediments mixed with small amounts of thermogenic gas and migrated as a result of focused fluid flow to form highly concentrated gas hydrates in the fine-grained sediments.

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