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ORIGINAL RESEARCH PAPER

Migration of methane associated with gas hydrates of the Shenhu Area, northern slope of South China Sea

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Abstract Shenhu Area is located in the northern slope region of the South China Sea. Pre-drilling reservoir prediction by the analysis of both 2D and 3D seismic data indicates the presence of hydrate-bearing sediments of approximately 70 m thickness. Data also suggests a strong spatial correlation between gas hydrates and gas chimneys. Evidence suggests that these gas chimneys created pathways for the migration of gas and fluids into the gas hydrate stability zone (GHSZ). In this study, we analyze reflection seismic data collected in the vicinity of a well where an abundance of gas hydrate is known to exist. Between the base of the gas hydrate stability zone and the top of the gas chimney, a thin layer of fine grained sediments is observed. A number of small faults (and possibly additional micro-fractures) breach the stratum and connect the gas chimney and GHSZ directly. Fluids, including free gas, may migrate upwards through these fractures. Additionally, small faults within the flanks of the gas chimney may effectively promote gas migration to the GHSZ. Amplitude variation with offsets analysis and instantaneous frequency analysis provided evidences of fluid pathways. A low-frequency anomaly over the center of the gas chimney indicates high seismic attenuation. This is interpreted to be caused by the migration of fluids (probably methane). Based on the results of this study, we propose an exploration for the origin of formation of Shenhu Area gas hydrate formation through the migration of methane.

Keywords Shenhu Area · Gas hydrate · Gas chimney · AVO analysis · Instantaneous frequency

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Introduction

Gas hydrates are crystalline solids that are formed when water molecules trap gas, commonly methane, within a crystal lattice cage (Sloan 1990). They are formed when pore fluids are saturated with methane at appropriate low temperature and high-pressure conditions. They commonly occur in marine sediments where water depths exceed 500 m. The most common indicators for marine gas hydrates are bottom simulating reflections (BSRs), reflections that are sub-parallel to the seafloor and that are commonly associated with free gas beneath the base of the gas hydrate stability zone (BGHSZ). At Shenhu Area, an offshore region on the northern slope of the SCS (Fig. 1), prominent BSRs indicate the presence of gas hydrates (Yao 2001).

Geophysical anomalies, including BSRs and amplitude blank zones, were identified at Shenhu Area during previous studies (Wu et al. 2013; Xu et al. 2006, 2010). In addition, plumes and pockmarks associated with gas seeps

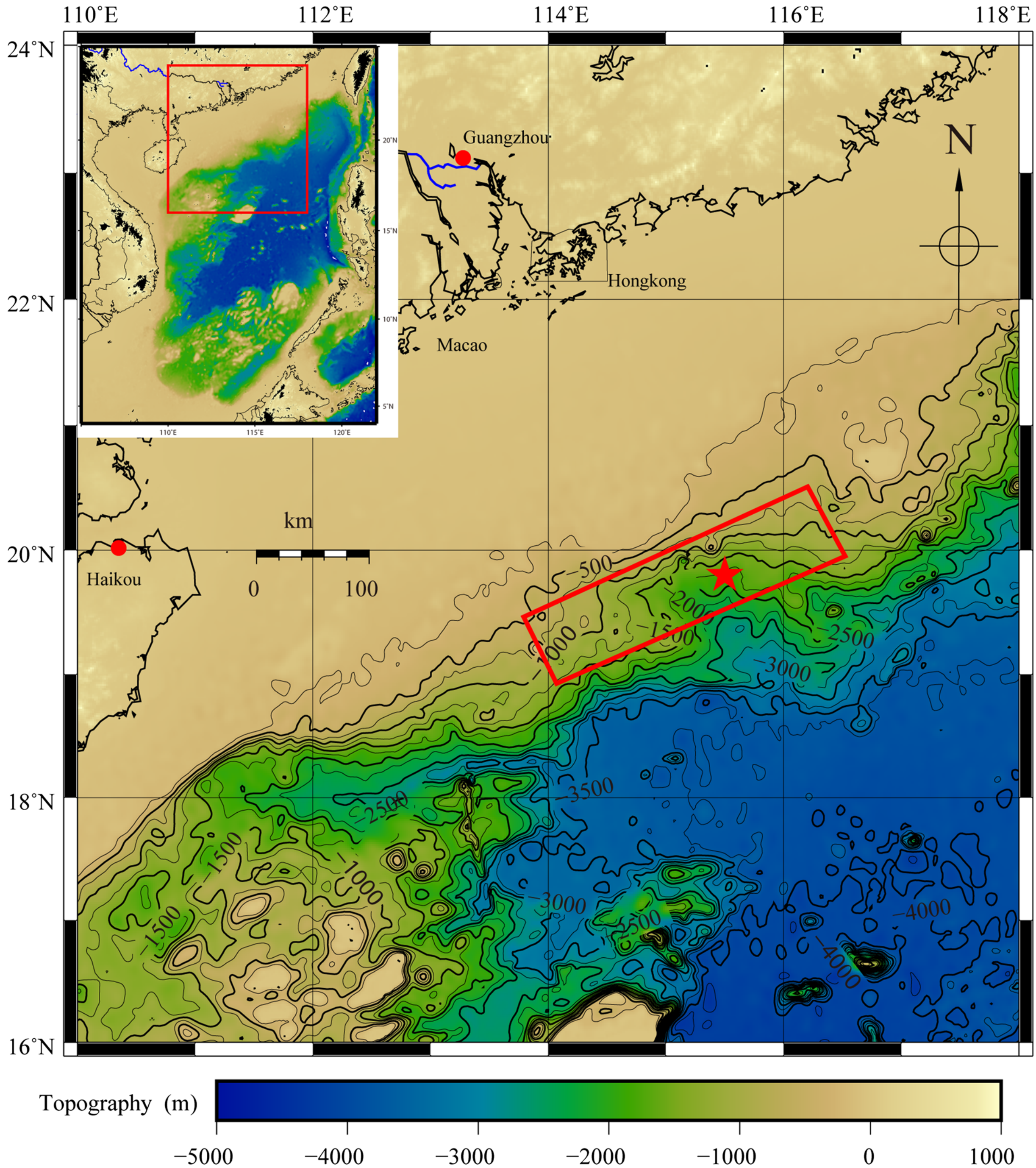

Fig. 1 The location of the study area. Shenhu Area (*red box*) is located southeast of the north slope of the South China Sea (SCS). The *red star* represents the Shenhu Area used in this study

have also been documented (Xu et al. 2010). All these observations indicate the presence of gas hydrates in this region. However, the migration of methane through the gas hydrate stability zone (GHSZ) is not yet well understood. Analysis of three-dimensional (3D) seismic data and multibeam data from the Pearl River Mouth Basin reveals numerous fluid flow features and associated widespread shallow gas from the depth of 500–2,000 m (Sun et al. 2012a, b). Gas hydrates occur within units of clayey slits and silts that contain abundant calcareous nannofossils and foraminifer. On a macro scale, gas chimneys, faults, and fractures, all identified in the seismic data, provide pathways for fluid migration into the GHSZ (Wang et al. 2011). There are indications that free gas is able to migrate along faults in the northwest and northeast of Shenhu Area (Su et al. 2014), however this is not yet well constrained. Gas chimneys may more precisely be referred to as 'fluid diapirs' as they do not break through seabed. However, following previous convention and given their shape and role in fluid migration, for the purposes of this study the term 'gas chimney' is employed.

Between April and June 2007, the China Geological Survey (CGS) and the Ministry of Land and Resources of the People's Republic of China carried out the first gas hydrate drilling expedition in the Shenhu Area. A total of eight boreholes were drilled and gas hydrate was revealed in the core samples from 3 sites (SH2, SH3, and SH7) (Wu et al. 2008). At SH2, the thickness of hydrate-bearing sediments is approximately 20 m. The level of gas hydrate saturation is calculated from pore water freshening and at its maximum reaches 48, 25 and 44 % (v/v), respectively at SH2, SH3, and SH7 (Wu et al. 2007). The hydrate-bearing sediment zone is located within 10–25 m above the BSR (Wu et al. 2010). In this study, attribute analysis of seismic reflection data in Shenhu Area is described. On the basis of these analyses, we propose an exploration for the migration of methane associated with the gas hydrates at Shenhu Area.

Geologic setting

The continental margin of the SCS developed during the Cenozoic. The western part of the SCS is a slip fracture zone and the east is a subduction zone of Manila Trench (Taylor and Hayes 1980). With an area of about $350 \times 104\ km^2$, it is the largest marginal sea of Western Pacific. The northern slope of SCS is a passive continental margin. After years of prospecting, three oil and gas bearing basins are located in there, including the Qiongdongnan Basin, the Pearl River Mouth Basin, and the Taixinan Basin (Wu et al. 2009a, b, c).

Shenhu Area is located in the southeastern part of Pearl River Mouth Basin (Fig. 2). Water depth is approximately 900–1,500 m and the seabed dips towards the southwest. The region has high sedimentation rates and houses thick sediment sequences, including the Wenchang and Enping Formations (Shi et al. 2009), both Paleogene in age and exhibiting organic matter contents of 0.46–1.9 % (McDonnell et al. 2000). There are two main regional fault systems oriented in the NE and NW directions, respectively. In addition, numerous small faults have been identified in shallow sediments. Multiple diapirs with different sizes, plumes, and pockmarks associated with gas seeps, penetrate the deep sediment (Wu et al. 2009a, b, c). The geologic setting, the water depth (which controls the temperature–pressure regime), and the methane-generating potential of the Shenhu Area indicate a suitable setting for gas hydrate accumulation (Wu et al. 2013) (Fig. 3).

Data and methods

The 2D and 3D seismic profiles analyzed in this study were collected by the "FENDOU SI HAO" of the Guangzhou Marine Geological Survey (GMGS) between 2005 and 2006. The vessel was equipped with a 160 cubic inch air gun array towed at a depth of 3 m below sea level. Shots were fired at intervals of 25 m. Seismic data were acquired with 3,000 m streamers at a depth of 5 m, with the spacing between the common depth points (CDP) of measurement being 12.5 m. To ensure full fold data acquisition, seismic records with a duration of 6 s were acquired with a sample rate of 1 ms. The effective bandwidth was between 40 and 120 Hz. In order to produce high-resolution seismic profiles, the raw seismic data were processed, including initial filtering, predictive and surface-consistent deconvolution, velocity analysis, dip-moveout (DMO), stacking, and prestack Kirchhoff time migration.

Amplitude variation with offsets (AVO) analysis was performed in the pre-stack domain. The raw data were bandpass filtered in the frequency domain between 12 and 140 Hz. Predictive deconvolution (with an operator of the length of 180 and prediction length of 16 ms) and surface-consistent deconvolution (factor length of 160 ms) were applied in order to increase resolution of the data, and reliability of interpretation. After amplitude-preserved processing, pre-stack Kirchhoff time migration was performed using root mean square (RMS) velocity.

The AVO theory depends on the contrast between P- and S-wave velocities (Diaconescu et al. 2001; Løseth et al. 2009). Seismic P-waves are sensitive to the presence of pore-fluids. Small amounts of free gas in sediment pore spaces would significantly decrease the P-wave velocity. Therefore, layers in the seismic section showing strong reflections may indicate the presence of free gas (Dewangan and Ramprasad 2007). Free gas is also known to cause attenuation of the high frequency components of seismic waves. Instantaneous frequency is a metric suitable to detect high attenuation regions, including free gas zones and gas chimneys. High frequency energy is strongly attenuated by sediments that contain free gas in pore spaces, resulting in a decrease in instantaneous frequency (Coren et al. 2001).

The effect of gas hydrates and free gas on seismic attenuation has not been studied in detail in Shenhu Area. Solid gas hydrates have a P-wave velocity of about 3.27 km/s compared to 1.5 km/s of water (Hu et al. 2010; Taylor et al. 2000). It is commonly assumed that the seismic velocity of the hydrate-bearing sediments is higher,

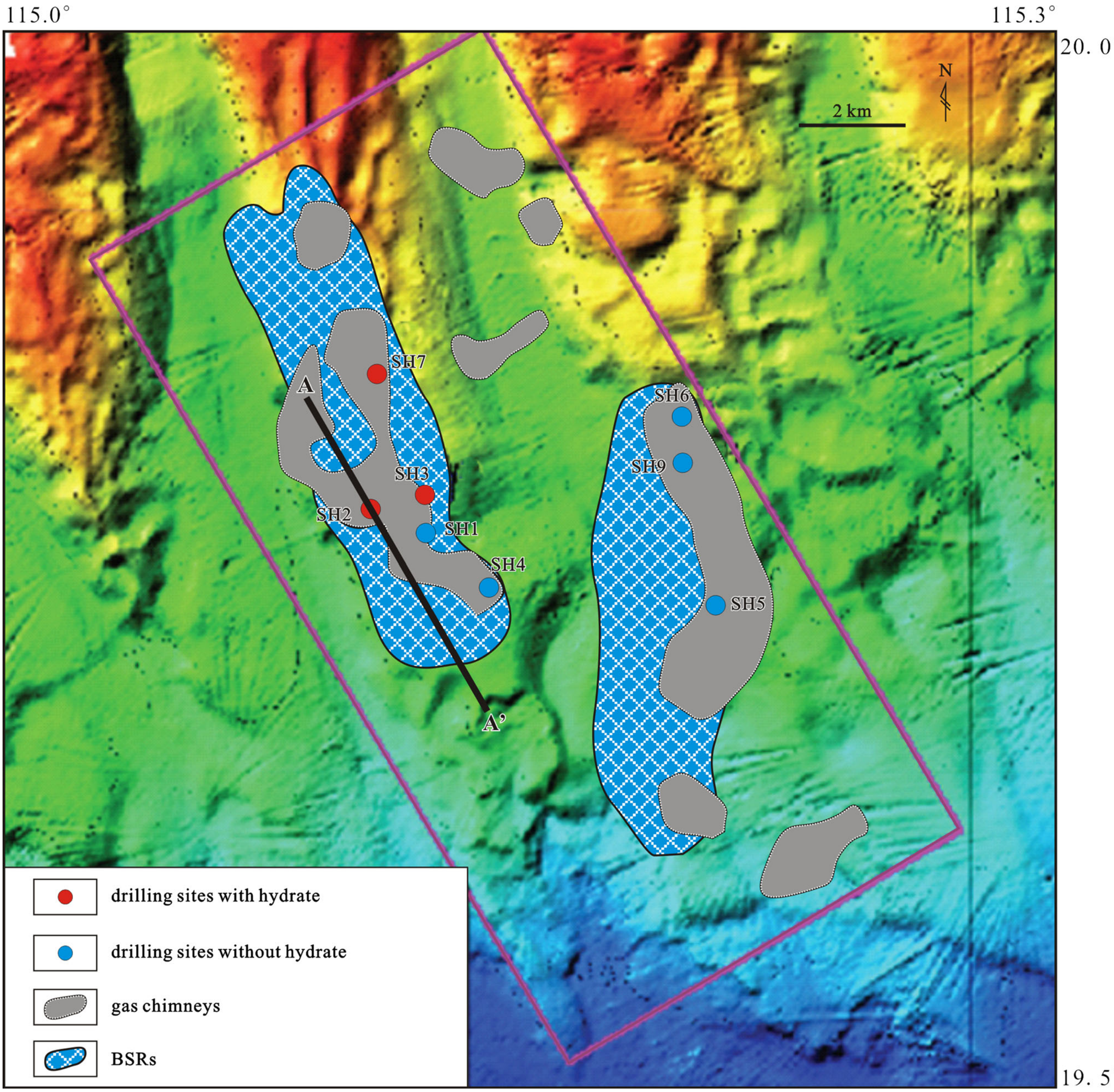

Fig. 2 The Shenhu Area and drilling sites location map. Areas of BSRs and gas chimneys are *outlined*. There are eight sites here, including SH2, SH3 and SH7, where gas hydrate samples were obtained. The line AA′ is a 3D line above the SH2 site. *BSRs* bottom simulating reflectors

and the value of velocity depends on the saturation and microscopic distribution of gas hydrates within the sediment pores. Wu et al. (2009a, b, c) and Xu et al. (2010) reported an increase in attenuation in the Shenhu Area gas hydrate zone. However, their observations are in contrast with theoretical predictions of velocity increase within the free gas-bearing sediments. Therefore, the strength of reflected waves traveling through the free gas zone should be severely attenuated. AVO and instantaneous frequency analyses, thus, helps distinguish zones of free gas accumulation beneath gas hydrates and the associated methane migration paths.

Observations and results

Seismic structure

Seismic profiles (Fig. 4) reveal localized doming and a fault system that extend up into the shallow sediments,

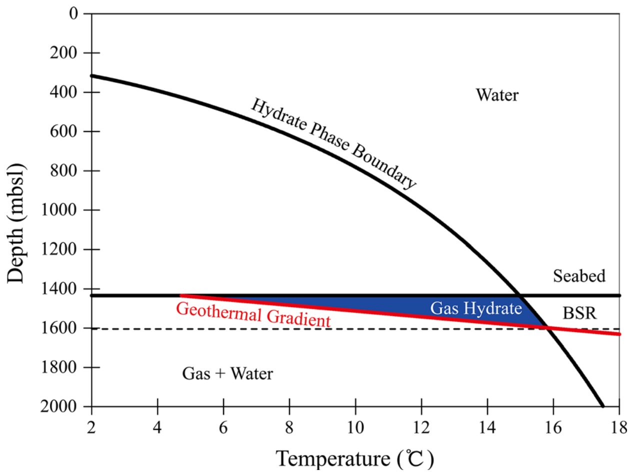

Fig. 3 Phase diagram of Shenhu Area. It was calculated using Miles equation (1995) with data in-site

above the crest of the interpreted gas chimney. The results of this study suggest that shallow sediment is actually the result of sediment waves, formed by contour currents up against the slope, and not slumps (Damuth 1979; Gong et al. 2012; Kuang et al. 2014). The BSR is almost parallel to the seabed and displays an irregular appearance that suggests strata dip through the BGHSZ. The deformation of BSR was interpreted to be caused by the presence of SW dipping strata terminations. It was inferred to have formed as a result of the sealing of the up-dip end of gas-bearing strata by gas hydrate-bearing sediments (from about 1.8 to 2.0 s). Above the gas chimney, there is a thin uniform stratum, between CDPs 550–700, that contains numerous small faults. They were good channels for gas to migrate into GHSZ.

AVO response to free gas and gas hydrate

Pre-drilling forecasts predicted that Shenhu Area gas hydrates would primarily be distributed within shallow sediments and in the free gas zone beneath the GHSZ, thought to be approximately 50–200 m in thickness (Wu et al. 2007, 2013). AVO analysis of seismic sections confirms that P-wave velocity (V_p) is very sensitive to gas saturation. High reflectivity may indicate increasing gas concentration due to free gas accumulation across layer boundaries.

There is a clear increase in the reflection coefficient of free gas-bearing formations in Line AA′ with a clear and continuous top interface evident (Fig. 5). Also within this profile, the distribution and thickness of the free gas-bearing layer is easily observed. The top interface of the free gas zone is at approximately 2.3 s. This provides a clear indication that the free gas zone is positioned underneath the GHSZ. It could thus be inferred that the upward migration of gas corresponded to the formation of the free gas layer underlying the gas hydrates.

It is assumed that accumulation of gas hydrates in higher-porosity strata would result in an increased seismic velocity. As a result, the velocity contrast between low and high porosity strata would be reduced. In turn, this would effectively reduce the reflection strength in the gas hydrate

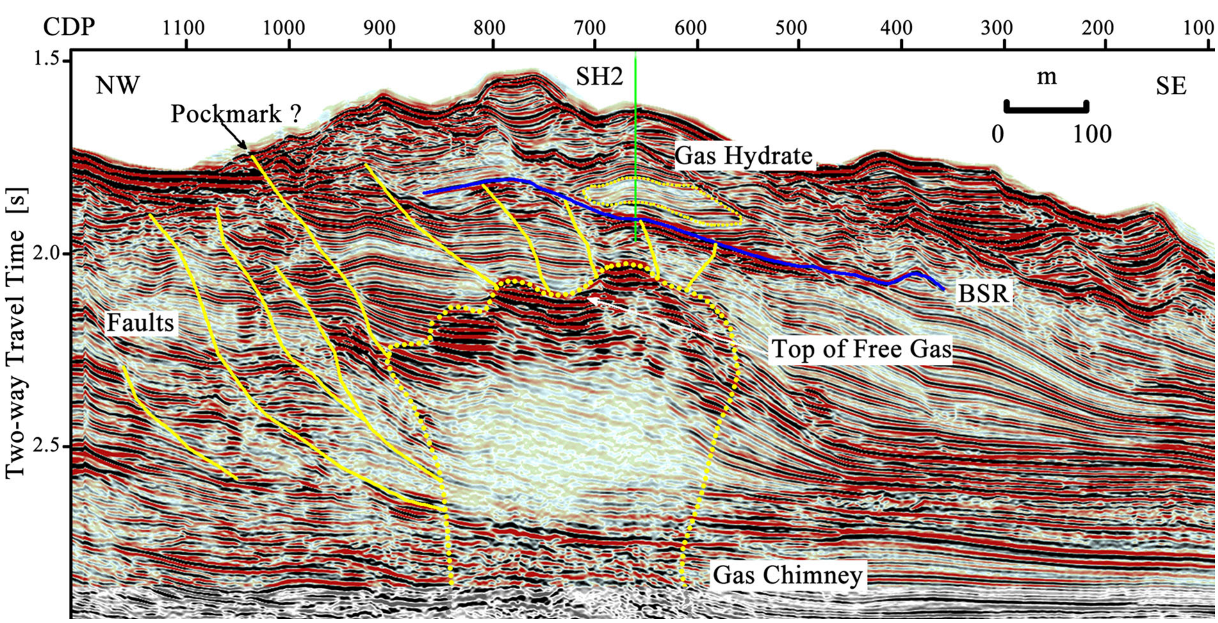

Fig. 4 A migrated profile along line AA′. This line was above the gas chimney beneath the SH2 site. Gas chimney, faults and BSR were interpreted. Areas associated with hydrate accumulations are revealed by drilling. Below the BGHSZ a set of very strong reflections probably defines prominent gas accumulations. *BGHSZ* base of gas hydrate stability zone

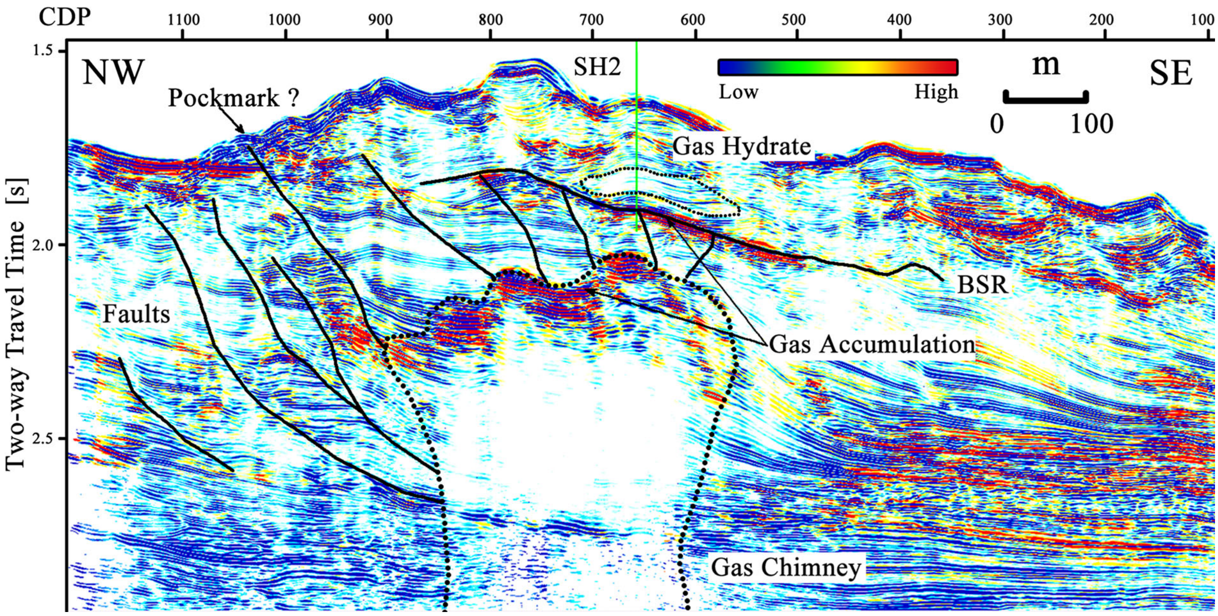

Fig. 5 AVO analysis plot for line AA′. High (*red*) and low (*blue*) reflection strength represented AVO responses of seismic data, respectively. Notice prominent gas reservoir below BGHSZ and enhanced reflection elements at the top of gas chimney. The hydrate stability zone is apparent because of blanking reflection at section of the line near CDP 650, ~1.8 s TWTT. *AVO* amplitude versus offset, *CDP* common depth point, *TWTT* two-way travel time

bearing sediment sections and result in a blanking zone in AVO analysis sections.

Instantaneous frequency

The instantaneous frequency plot of seismic data for line AA′ (Fig. 6) displays high and low frequencies represented by reds/yellows and greens/blues, respectively. The analysis of instantaneous frequency data for Line AA′ indicates that a shift to lower frequencies occurs beneath 2.1 s TWTT. Low-frequency "shadows" are indicative of high absorption in the overlying strata. Gas bearing strata cause high absorption levels and a sharp drop in V_p. At lower frequencies, and hence larger Fresnel zones, reflections appear continuous. Low-frequency "shadows" are, therefore, commonly associated with free gas if they occur beneath highly reflective layers indicating strong velocity contrasts (Taylor et al. 2000). The results suggest that the shift to lower frequencies beneath the BSR is associated with free gas. Above the gas chimney, between CDPs 580–710, a narrow horizontal layer extends to the BSR. There is a lateral shift to higher frequencies adjacent to the anomaly along individual reflections and a decrease in frequency values with depth. This low-frequency anomaly correlates with high reflection strength anomalies. This observation is consistent with the suspected presence of free gas accumulations within the fault system. Additionally, the sediments above the zone of highly reflective free gas-bearing strata may be the reason for the relatively low reflectivity in the gas hydrate zone.

The low-frequency zone, observed at CDPs 550–910 and TWTT 2.1–3.0 s, is interpreted to be a gas chimney beneath gas hydrates. The frequency within this region is significantly lower than that of the surrounding material. Faults around the low-frequency zone provide effective pathways for gas migration. Faults on the left flank of the gas chimney help to facilitate free gas migration upwards toward the seabed (where they can escape). These faults, located above the low-frequency zone, allowed methane to enter the GHSZ, a necessary step in the eventual formation of gas hydrates.

Discussion

Gas chimneys in Shenhu Area are mainly confined to the northwest and southeast of the region. The geological setting provides three possible causes of vertical fluid migration and the subsequent formation of the gas chimneys: (1) a high subsidence rate and the presence of fine-grained sediment; (2) the simultaneous formation of huge effective source beds, e.g., the Enping and Wenchang Formations (Pang et al. 2004), that provide sufficient material for fluid overpressure.

Shenhu Area is an example of a region actively undergoing forced advection of methane rich fluids that

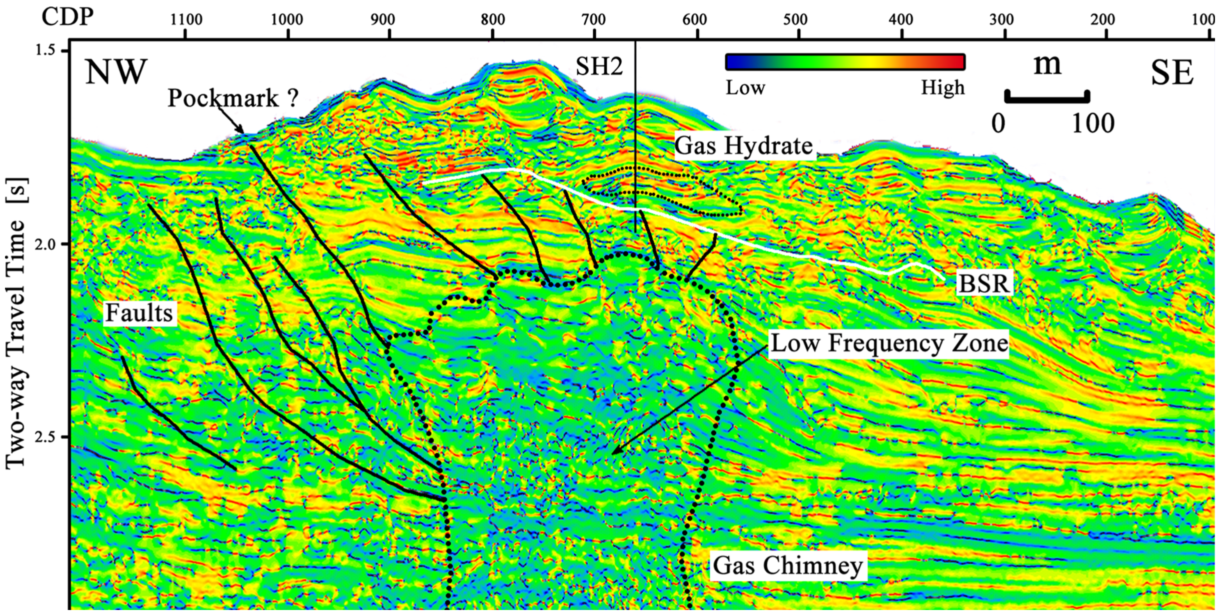

Fig. 6 Plot of instantaneous frequency for line AA′. Attenuation of higher frequencies near CDP 700, ~1.8 s TWTT, is coincident with enhanced reflection elements in Fig. 4. Low frequency shadows also occur below reflections with high reflection strength values, between CDPs 600–900

are escaping into the GHSZ through gas chimneys and faults system (Sun et al. 2012a, b). Gas chimneys have commonly been considered the most important pathways for fluid migration (Cathles et al. 2010; Davies and Clarke 2010; Nourollah et al. 2010; Nyamapfumba 2011; Sun et al. 2012a, b). On this basis, fluid flow at Shenhu Area would be interpreted as the flow of thermogenic gases from the Wenchang and Enping Formations, with gas hydrates forming due to the accumulation of these gases. However, geochemical analyses of headspace and dissolved gases and the carbon isotope of gas hydrate samples suggested that the gas in the gas hydrates is primarily biogenic in origin (Wu et al. 2009a, b, c). Chen et al. (2012) suggested that migration of gas (thermogenic methane and biogenic methane) could be divided into two periods, before and after the Miocene aged Dongsha Movement. The migration of thermogenic gas through the gas chimneys underlying the BSRs was induced by the release of overpressured fluid. This event was also the likely cause of the tectonic events of the Dongsha Movement. During the subsequent quiescent period, gas chimneys become inactive and the flux of thermogenic fluids decreased (Chen et al. 2012). However, the pathways still acted as conduits for gas migration and abundant biogenic gas from shallow sediments was transported to form highly concentrated gas hydrates in the fine-grained sediments (Sun et al. 2012a, b).

Without regard to methane origin, the trapping and migration of the methane associated with the gas hydrates occurred primarily through "gas chimney–faults" (Fig. 7). As the primary channel, gas chimneys became predominant vertical migration route of methane. When it reached the shallow strata, methane migrated laterally along sealing layers. Vertical motion of methane was retarded, with small faults becoming the main channel of methane penetration. These small faults may have formed as a result of the tectonic movement or overpressure. Finally, the methane became trapped at the GHSZ.

Conclusions

On the basis of seismic reflection data analysis, we present 'gas chimney–fault' conceptual model to explain the migration of methane associated with the Shenhu Area GHSZ (Fig. 7). Seismic data from the area provide strong evidence that free gas is trapped beneath the up-domed BGHSZ and above the gas chimneys, although, there are other possible explanations for these seismic signatures; our analyses strongly support the hypothesis that this gas is escaping upward along faults through the GHSZ. The evidence in support of this interpretation includes: (1) seismic data showing "enhanced reflections", anomalously strong reflection events that correlate well with fault pathways above gas chimneys and that may result from strong acoustic impedance contrasts generated at gas pockets and; (2) attenuation of higher frequencies along small faults above the gas chimneys, resulting in vertically decreasing values for frequency anomalies, consistent with the presence of gas and/or fluids.

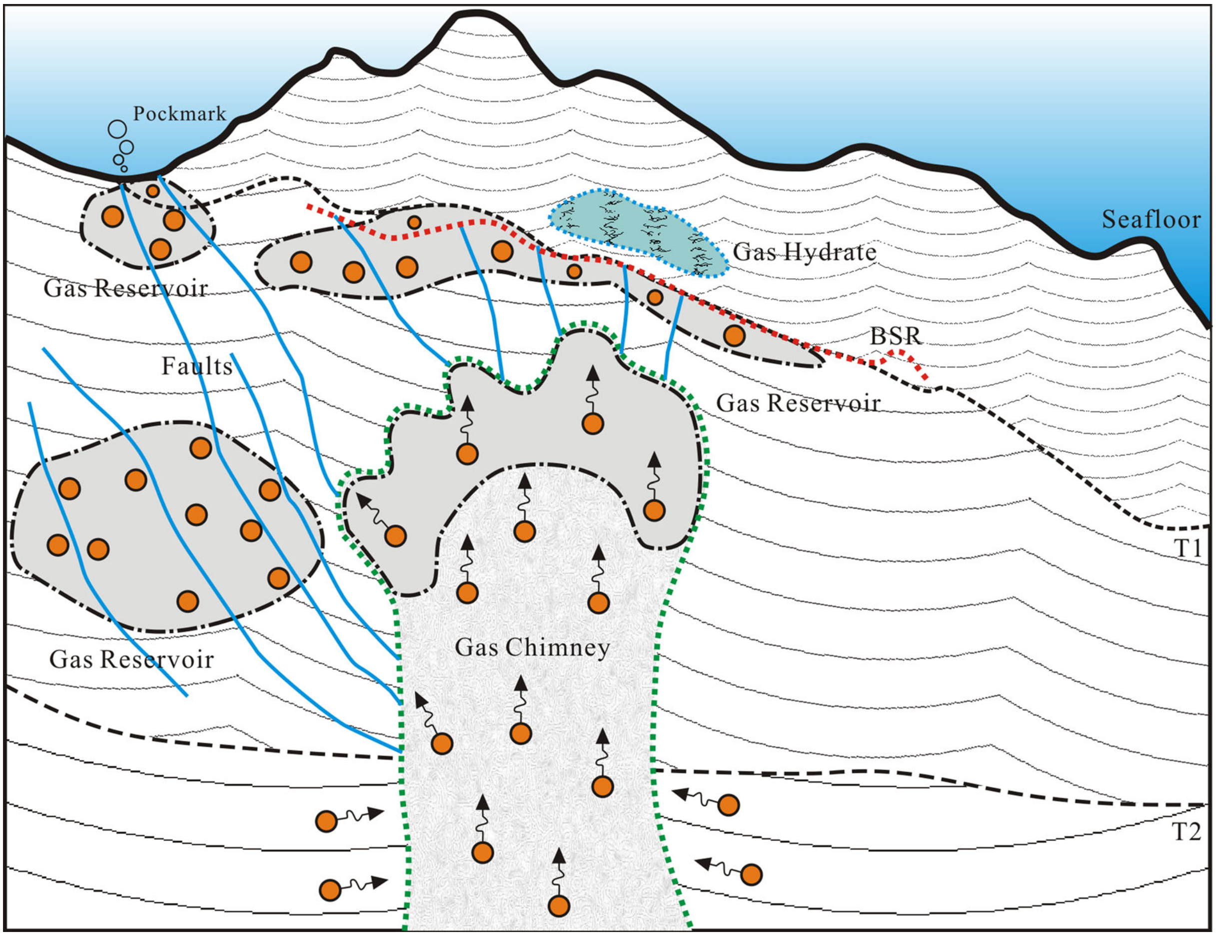

Fig. 7 The "gas chimney–faults" schematic diagram of trapping and migration of methane associated with the gas hydrate at the Shenhu Area. *T1* and *T2* represented boundaries of different strata classified by geologic periods

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