Hindawi
Geofluids
Volume 2022, Article ID 1954931, 19 pages
https://doi.org/10.1155/2022/1954931

WILEY | Hindawi

Research Article

Natural Gas Migration Pathways and Their Influence on Gas Hydrate Enrichment in the Qiongdongnan Basin, South China Sea

Tingna Zuo ,[1,2] Ren Wang ,[1,2] Yulin He ,[3,4] Wanzhong Shi ,[1,2] Jinqiang Liang ,[3,4] Litao Xu ,[1,2] Hao Du ,[1,2] Yan Deng ,[1,2] and Xiaofeng Xu [1,2]

[1]*Key Laboratory of Tectonics and Petroleum Resources, Ministry of Education, China University of Geosciences, Wuhan 430074, China*
[2]*School of Earth Resources, China University of Geosciences, Wuhan 430074, China*
[3]*Southern Marine Science and Engineering Guangdong Laboratory, Guangzhou 511458, China*
[4]*Guangzhou Marine Geological Survey, China Geological Survey, Guangzhou 510075, China*

Correspondence should be addressed to Ren Wang; rwang@cug.edu.cn and Yulin He; heyulin200910@163.com

Received 24 June 2021; Revised 30 September 2021; Accepted 7 April 2022; Published 27 May 2022

Academic Editor: Andrea Brogi

2D and 3D seismic data and basin simulation were used to investigate the gas hydrate distribution and natural gas migration pathways in the Qiongdongnan Basin (QDNB). Hydrate-related amplitude anomalies and extensive bottom simulating reflectors (BSRs) were mapped within the uppermost part. Based on their seismic reflection characteristics, the three main types of natural gas migration pathways and their distributions in the QDNB were identified through high-resolution seismic data. Basin modeling was carried out to document the migration efficiency of different migration pathways and their effects on hydrate enrichment. The basin modeling results show the following: (1) Diapirs, fault structures, and fractures constitute the three main types of natural gas migration pathways that transport the thermogenic gas from the deep to shallow layers in the QDNB. (2) The three migration pathways impact hydrate enrichment in different ways. Diapirs and faults contribute significantly to hydrate enrichment due to their higher migration efficiency. In comparison, the migration efficiency of the fracture systems is lower, with minimal benefit to hydrate enrichment. (3) The natural gas hydrate in the QDNB is mainly distributed along the diapirs and deep faults and generally scattered around the fracture system. These conclusions indicate that the migration pathways in the QDNB are regionally distributed and are closely related to hydrate accumulation.

1. Introduction

Gas hydrates, also known as methane hydrates, are ice-like crystalline solids in which gas (mostly methane) is trapped within a water cage under high-pressure and low-temperature conditions [1]. Since 1999, natural gas hydrate surveys have been conducted on the northern slope of the South China Sea (SCS) in China. Research has been carried out on the macroscopic geological conditions, such as the influence of tectonic activity, sedimentary environment, temperature and pressure conditions on the gas saturation, burial depth, and distribution of hydrate reservoirs [2–5]. In some studies, geological and geophysical data have been used to study the evolution of reservoir-forming processes [6, 7].

The migration pathway is the key controlling factor for petroleum accumulation in conventional reservoirs [8, 9], which can be identified through the reflection characteristics on the seismic profile. Migration is crucial for the formation and accumulation of natural gas hydrate, since most of the gas source of hydrates comes from deep thermogenic gas. Globally discovered hydrate enrichment areas have confirmed that the natural gas migration pathways are composed of faults and diapirs [10–12]. Mud diapirs and gas chimney structures developed in the Nankai trough and the Yuling basin of Korea, directly control the distribution

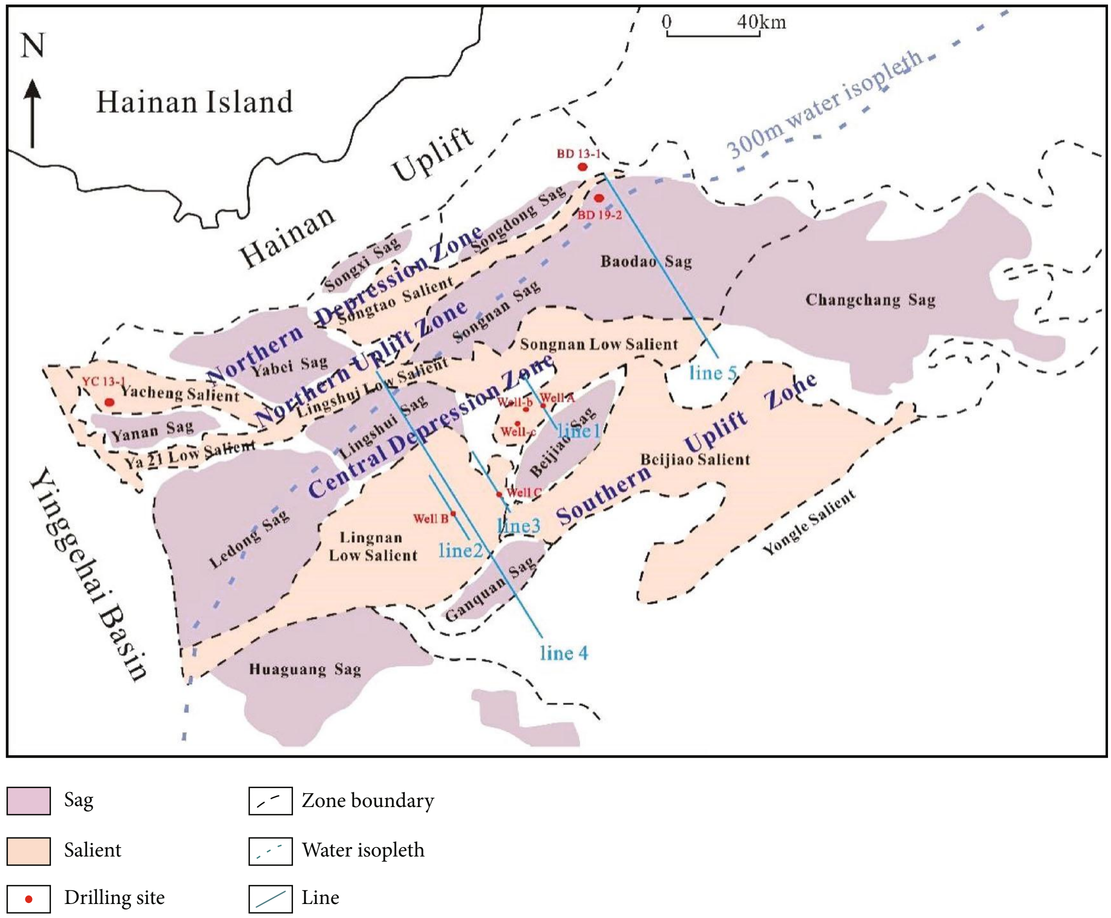


Figure 1: The location and tectonic divisions of the QDNB, SCS (modified from [17]).

of natural gas hydrate, whereas fault systems control hydrate formation in the Gulf of Mexico, USA [12–15]. In the SCS, some studies found that hydrate enrichment is related to diapiric structures, faults, and unconformities [4, 10, 16, 17]. Furthermore, fluid migration pathways such as faults and fractures, submarine slumps, mud diapirs, and gas chimneys are relatively common in the north SCS [7]. Xu et al. (2021) proposed that the fluid migration pathways developed in the QDNB include gas chimneys, diapir structures, and faults (including synsedimentary faults) [18]. There are many kinds of migration pathways in QDNB, but the diapir structure and fault systems mainly controlled the fluid migration in the basin.

Different types of migration pathways have different effects on hydrate saturation and accumulation. Su et al. (2014) found that in the Shenhu area, SCS, the deep fluids flowed rapidly upward along a high-permeability fracture channel, forming a high-saturation natural gas hydrate in the gas hydrate stability zone (GHSZ) [19]. Other studies have shown that the migration pathways, GHSZ, gas source condition, and reservoir-forming characteristics are the theoretical basis for hydrate research [7, 17, 20]. These studies provide a good theoretical basis for gas migration and hydrate accumulation systems. In recent years, basin modeling has been widely used in hydrate research, and 2D and 3D models have been used successfully to reproduce hydrate distributions inferred from seismic data [21–24]. For example, Su et al. (2014) reconstructed the gas generation, migration, and accumulation process by restoring the burial history and thermal evolution history of the basin and analyzed the petroleum generation potential of organic matter in sediments and its contribution to gas hydrate accumulation. In addition, a 2D-restored structural model was used to simulate gas hydrate properties over time, focusing on the presence and extent of the GHSZ [25]. Kroeger et al. (2019) investigated the mechanisms for gas hydrate formation and resulting hydrate distribution using a 3D model of the southern Hikurangi Margin, New Zealand. Therefore, it is feasible to use basin modeling technique to simulate the process of deep fluid migration and gas hydrate formation.

The QDNB has been proved to have enormous gas hydrate resource potential, but it is still in the early stage of gas hydrate exploration. Previous studies on the gas migration pathway are only limited to the reflection characteristics description [17, 20, 26–28]. Still, the influence of different migration pathways on the dynamic process of gas migration and hydrate enrichment has not been considered, which limits the understanding of the timing, mechanisms, and abundance of gas hydrate formation. In this study, the seismic interpretation and dynamic basin modeling have been integrated to study the seismic reflection characteristics and migration efficiency of different types of natural gas

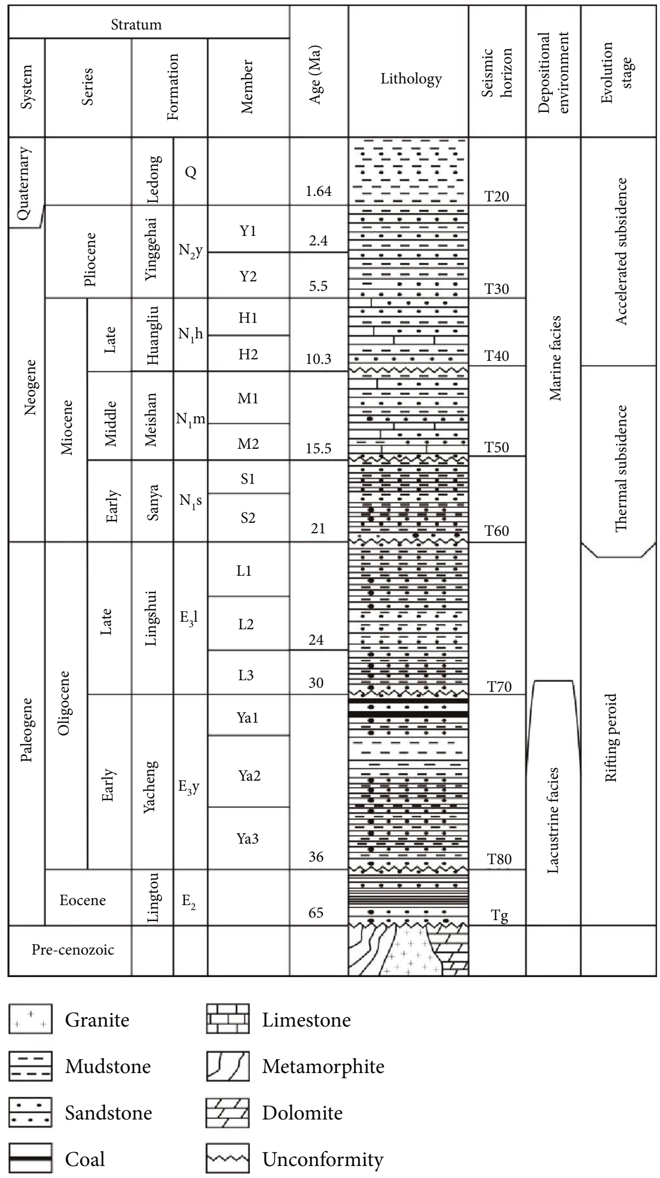


Figure 2: Generalized stratigraphic column of the QDNB (modified from [30, 31]).

migration mechanisms and their influence on hydrate accumulation in the deep-water area of the QDNB, so as to provide a useful guideline for the evaluation of high-saturation hydrate accumulation area in the basin.

2. Geological Setting

The QDNB is located in the northwestern continental margin of the SCS, covering an approximate area of 3.8×10^4 k m^2 [19]. Several uplifts and depressions are distributed across the basin. The basin consists of four primary structural units, including the northern depression zone, northern uplift zone, central depression zone, and southern uplift zone, which can be further divided into more than 20 tertiary structural units (Figure 1) [29].

The QDNB experienced rift (Eocene-Oligocene) and depression stages (after the early Miocene), with a typical "two-layer" structural pattern (Figure 2) [30, 32]. During the rifting period, with intense tectonic activities, it generated a lot of faults and mud diapirs. On a basinal scale, many magmatic diapirs occurred in the western central depression and the southern uplift in the deep-water area of the basin (Ledong sag and Lingshui sag, and Songnan Low Salient areas) [17, 33, 34]. In contrast, in the eastern part of the basin, a large number of faults were developed in the Baodao and Changchang sags, without diapirism. Basement faults are widely distributed in the basin, with generally three groups trending nearly EW, NE, and NW [35–37]. Moreover, the structural layer of depression represents the deposition in the thermal subsidence period. During the postrifting stage, the basin subsided with minor additional faulting [38].

Extensive studies show that sedimentary environment, reservoir properties, and source rock conditions have a significant impact on oil and gas reserves [26, 31, 39–42]. The sedimentary strata in the basin include the Eocene, the

Table 1: Lithologic data for sequences of line 1 in the study area [50].

Reflecting interface	Sedimentary facies	Mudstone content	Sandstone content
TSB-T20	Bathyal-deep-sea deposits	99.35%	0.65%
T30-T20	Bathyal-deep-sea deposits	74.19%	25.81%
T40-T30	Bathyal-deep-sea deposits	81.85%	18.15%
T50-T40	Bathyal-deep-sea deposits	74.2%	25.8%
T60-T50	Bathyal-deep-sea deposits	94%	6%
T70-T60	Neritic deposits	96%	4%
Tg-T70	Nearshore subaqueous fan	54.3%	47.7%

Table 2: The parameters of the paleo-heat flow and paleo-water depth in the study area [50].

Age (Ma)	Water depth (m)	Age (Ma)	Heat flow (mW/m^2)
1.90	1600	0.00	72.00
5.50	1000	0.60	77.00
10.50	120	1.50	75.00
15.50	80	5.50	68.00
17.50	60	10.50	67.00
21.00	50	23.00	62.00
22.00	20	30.00	65.00
23.00	10	65.00	60.00
25.00	15	100.00	56.00
30.00	20		
50.00	15		
65.00	10		

Oligocene Yacheng and Lingshui Formations, the Miocene Sanya, Meishan, and Huangliu Formations, the Pliocene Yinggehai Formation, and the Quaternary Ledong Formation, bounded by the Sequence Boundary T80, T70, T60, T50, T40, T30, and T20 [26] (Figure 2). Previous studies revealed that the sedimentary environment in the Paleogene changed from the Eocene lacustrine to the Oligocene marine [26, 40] (Figure 2). Since the Miocene, moderately deep to deep-water marine sediments have been deposited, and after the Pliocene, a clear shelf-slope system has been gradually differentiated [17, 36]. Under these environmental conditions, three sets of source rocks are developed in the basin: (1) the Eocene lacustrine high-quality source rocks [41, 42]; (2) the Oligocene coastal plain, offshore, and shallow marine facies source rocks. The marine and continental transitional and shallow marine source rocks in the Yacheng Formation are mainly gas-generating, and the marine mudstones in the Lingshui Formation are secondary source rocks [17, 43, 44]; (3) the Miocene moderately deep to deep-water marine source rocks are also secondary source rocks but are in the immature to low maturity stage with respect to petroleum generation [45, 46].

3. Methods and Data

The dataset for this study includes 800 km^2 of recently acquired 3D seismic data and 5700 km of 2D seismic data within the QDNB. In the study, the software PetroMod™ v.2016 2D was used to simulate the study area's petroleum migration and hydrate formation process [47].

3.1. Model Construction. The seismic profiles through well A, well B, and well C are used to define the architecture of the model (Figure 1), which, respectively, represent different migration pathways: gas chimney (line 1), fault structure (line 2), and faults and fracture system (line 3) (the positions of the seismic profiles are shown in Figure 1). The stratigraphic framework is based on the interpretation of CNOOC for petroleum exploration and gas hydrate exploration for shallower sediments [48, 49]. Then, the faults, gas chimneys, diapirs, and mass-flow deposits were delineated in the stratigraphic framework to complete the construction of the basin model. The major gas chimneys and Meishan formations are represented by high permeable sediments, and faults are considered open faults in the model. The T2 and T3 models were chosen as the petroleum generation kinetic models corresponding to kerogen types II and III, and the petroleum saturation method was selected as the expulsion model [48].

3.2. Model Parameters

3.2.1. Geological Framework and Lithologic Parameters. The lithology model for shallow sediments (<300 m) is defined by the core descriptions and gamma-ray (GR) logs of well A, well B, and well C. The lithologies for deeper layers are based on the research results on regional sedimentary facies. In the process of lithology assignment of a given model layer, several different lithologies were mixed according to the statistical composition. Lines 1, 2, and 3 show some differences in lithologic assemblages. The depositional environment and sedimentary facies changed progressively in response to the paleotopography. Different depositional facies must be identified and assigned with other parameters. The proportion of sandstone for each formation in line 1 is listed in Table 1, derived from the research results of Kong (2010).

3.2.2. Erosion. The erosion parameters of the study mainly refer to the research data of Kong (2010). Referring to the previous estimation of erosion in a single well [50], combined with the geological reality of the QDNB, the thickness eroded during the unconformities T60, T40, and T70 was calculated to be 200-300 m, 100-300 m, and 100-200 m, respectively. The specific amount depends on the location and characteristics of each section.

3.2.3. Paleo-Heat Flow, Paleo-Temperature, and Paleo-Water Depth Parameters. Paleo-heat flows, paleo-temperatures, and paleo-water depths in this study were taken from the

Table 3: Geochemical parameters of source rocks in the study area [50–52].

Source rock age	TOC (%)	Proposed range of TOC content	HI (mg/g)	Kerogen type	Petroleum generation model	Remarks
Miocene	0.6	0.3-1.0	205	III	Burnham (1989)_T_3	The measured data of the sample
Oligocene	1.1	0.8-1.8	257	III	Burnham (1989)_T_3	[50, 52]
Eocene	2.34	2.0-2.5	450	II	Burnham (1989)_T_2	[50, 51]

research results of Kong (2010) (Table 2). The basin modeling software was used to calculate paleo-temperatures, and the simulated present-day temperature gradient was adjusted using the measured temperature gradient. The water depth also varied significantly in different areas and sedimentary periods. The paleo-water depths were extracted according to the sedimentary facies and sea-level change curves during different periods (Table 2) [50].

3.2.4. Organic Geochemical Parameters of Source Rocks. The organic geochemical parameters of source rocks mainly refer to the research data of Kong (2010). The main types of kerogen in the study are III and II [48], and the geochemical parameters of three sets (the Miocene, the Oligocene, and the Eocene) of source rocks are determined by reference to Kong (2010) (Table 3).

4. Results

4.1. Types and Characteristics of the Natural Gas Migration Pathways. Based on the detailed description and interpretation of seismic profiles in the key target areas, drilling and logging results of the QDNB, three main gas migration pathways, including magmatic diapirs and gas chimneys, fault structures, and fracture systems were identified in the basin.

Gas chimneys act as conduits for fluid transport and storage [53–55], which shows abnormal reflections on the seismic profile due to the vertical migration of natural gas or other fluids. As shown in Figure 3, there is a large-scale gas chimney structure in profile line 1, and the lower part of the gas chimney is a magmatic diapir (developed in Songnan Low Uplift). The gas chimney in this study area showed a pull-down, narrow, vertical column with fuzzy reflection or chaotic reflection interior, and the reflection events at the flanks of a gas chimney are also interrupted or terminated across the border of a gas chimney (Figure 3). What is more, gas chimneys often end at the BSRs. The occurrence of the BSRs with high amplitude and poor continuity is the most important and effective indicator of layered gas hydrate [5, 56–59]. As we can see in Figure 3, BSRs with strong amplitude, wide distribution, and reversed polarity with seabed are developed at the top of the gas chimney (Figure 3). In addition, the top of the gas chimney is usually blocked by the caprock, and the free gas widely accumulated under the caprock and around the gas chimney, as well as the deposition of shallow mass transport deposits (MTDs), leading to the lateral extension of the strong reflectors and the bright spots at the periphery of the chimney [17, 59–61]. In the seismic profile of line 1, the periphery of the chimney is surrounded by bright spots and strong amplitude reflection, and above the BSRs at the top of the gas chimney is the GHSZ (Figure 3).

Faulting is widely developed in the QDNB, and there are mainly interpreted based on high-resolution seismic profiles by recognizing abrupt changes in the continuity of seismic reflectors [61]. The seismic profile shows that the deep faults cut through the thick formations, connecting the deep and shallow stratum, and in the upper of the large faults, some BSRs and bright spots were observed (Figure 4). As shown in Figure 4, the BSRs in the upper faults showed a relatively high reflection magnitude and continuity (Figure 4), which often indicates the presence of hydrates. Due to the extensive accumulation of free gas and the deposition of MTDs, many bright spots with strong reflections can be observed at the top of faults. Besides deep faults, natural gas also accumulates and diffuses at the end of some shallow faults, forming bright spot reflections in seismic profiles (Figure 4). In sedimentary strata, fractures are produced by strata deformation, forming complex networks in the Earth's crust and serving as critical pathways for fluid migration in subsurface geological media [62–64]. The fracture system is hard to identify on seismic profile due to its small scale and chaotic characteristics. As is shown in profile line 3, some gas fuzzy zone related to the fracture systems can be observed above the T40 interface, with bright spots and BSRs distributed at the top zones (Figure 5).

4.2. Numerical Modeling Results. In the numerical simulation model, the density of the arrow was used to represent the amount of oil and gas migration to compare the migration efficiency of different natural gas migration pathways. The numerical modeling results show that the gas was generated from the deep coal-measure and lacustrine source rock from Yacheng and Lingshui formation, migrated along with the diapir/sediment interface and then vertically upwards, forming a gas chimney to the shallow sediments above (Figure 6(a)). The gas chimney migration pathway is characterized by continuous vertical gas distribution, sufficient gas supply, and high migration efficiency. Furthermore, large amounts of natural gas migrated upward along large faults, then accumulated and diffused at the upper end of the faults in profile line 1 (Figure 6(a)) and 2.5-7.5 km distance in profile line 2 (Figure 6(b)). But there are few faults in the lower part of well B, and only a small amount of oil and gas are migrated to the shallow layer (Figure 6(b)). The result of the simulation shows that the characteristics of deep fault are high efficiency, long distance, and relatively large-volume petroleum migration and

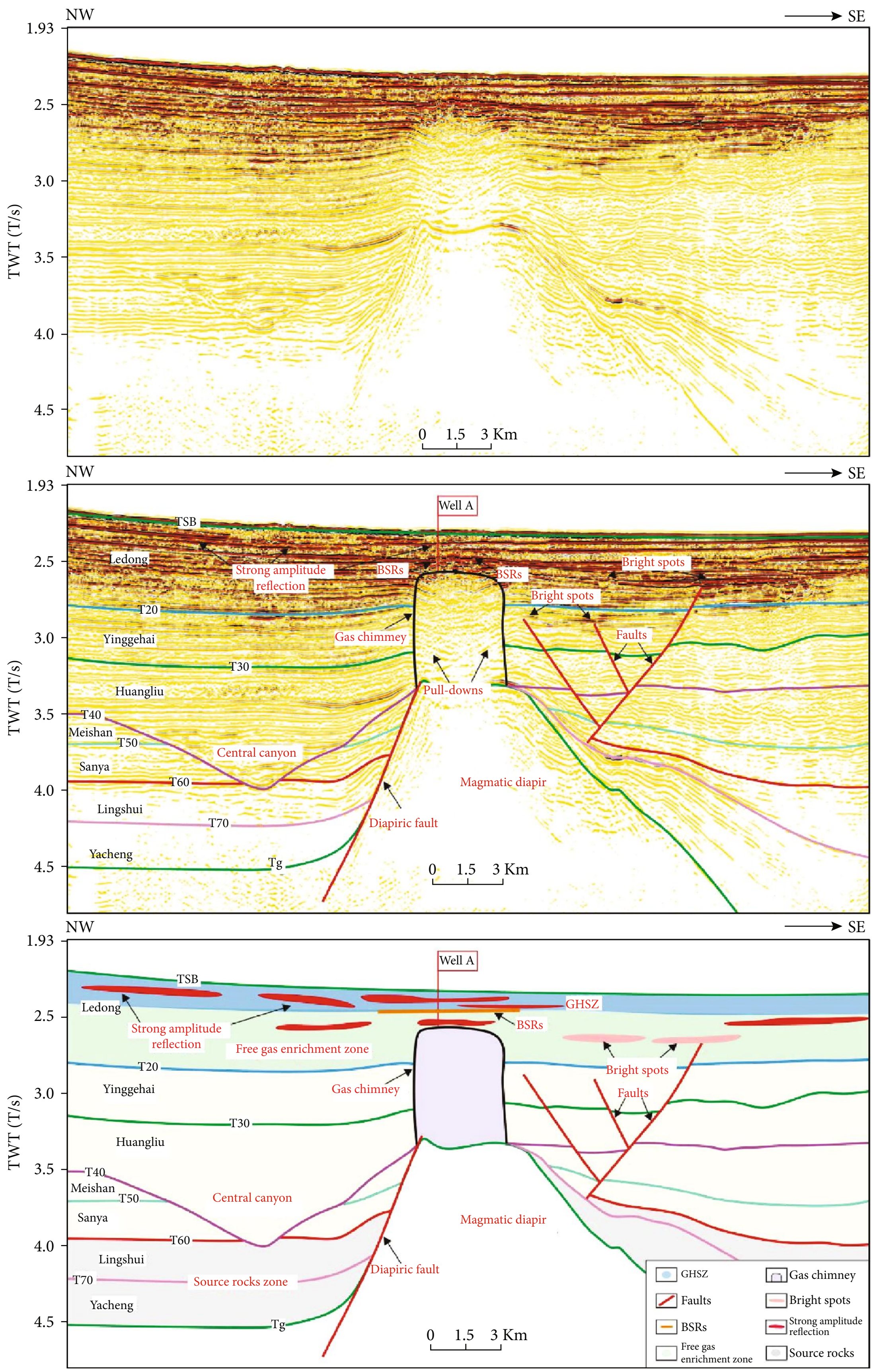


Figure 3: Gas chimney structure shown in the seismic profile of line 1 in the QDNB (profile location is shown in Figure 1).

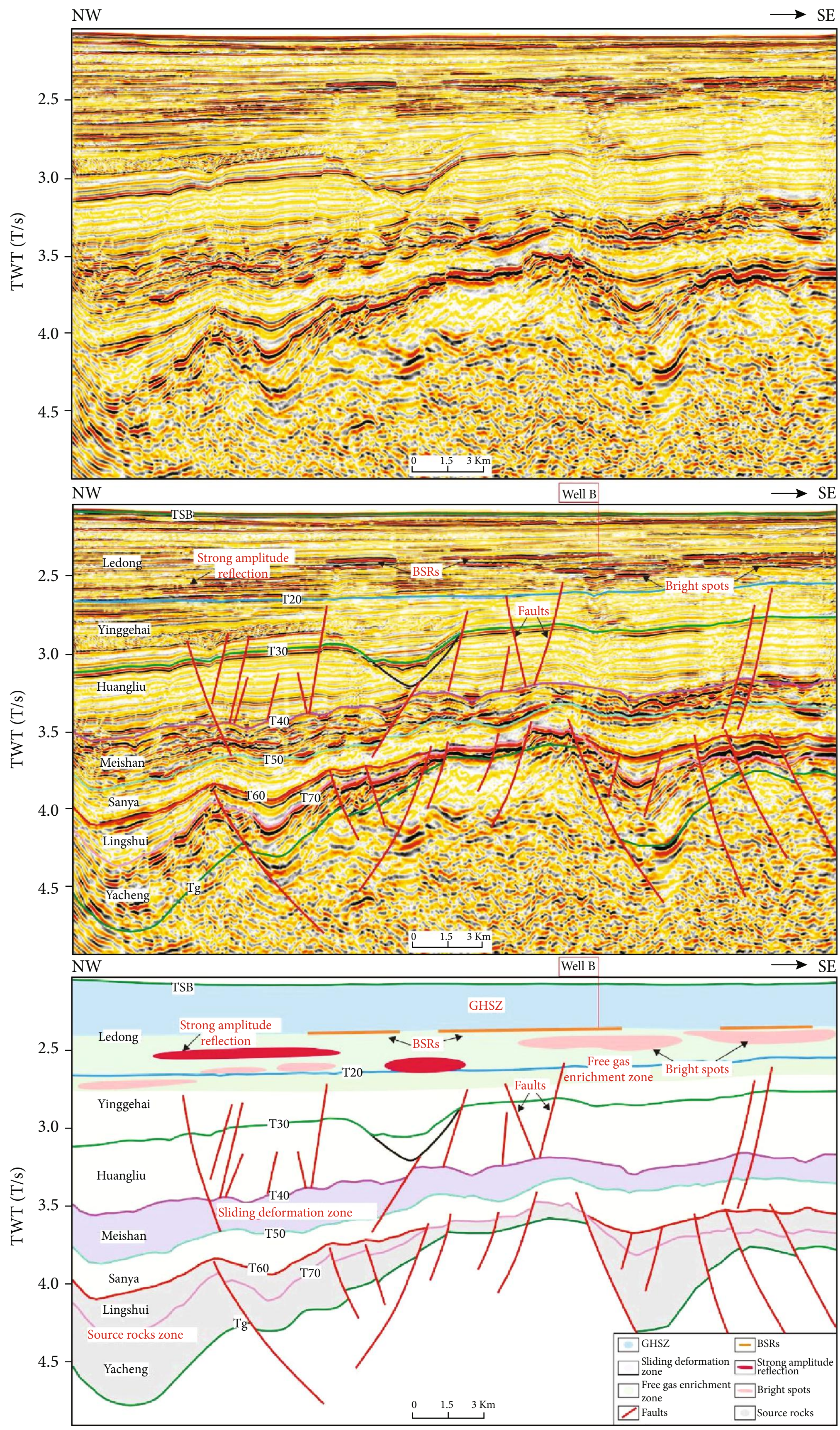


Figure 4: Fault structure shown in the seismic profile of line 2 in the QDNB (profile location is shown in Figure 1).

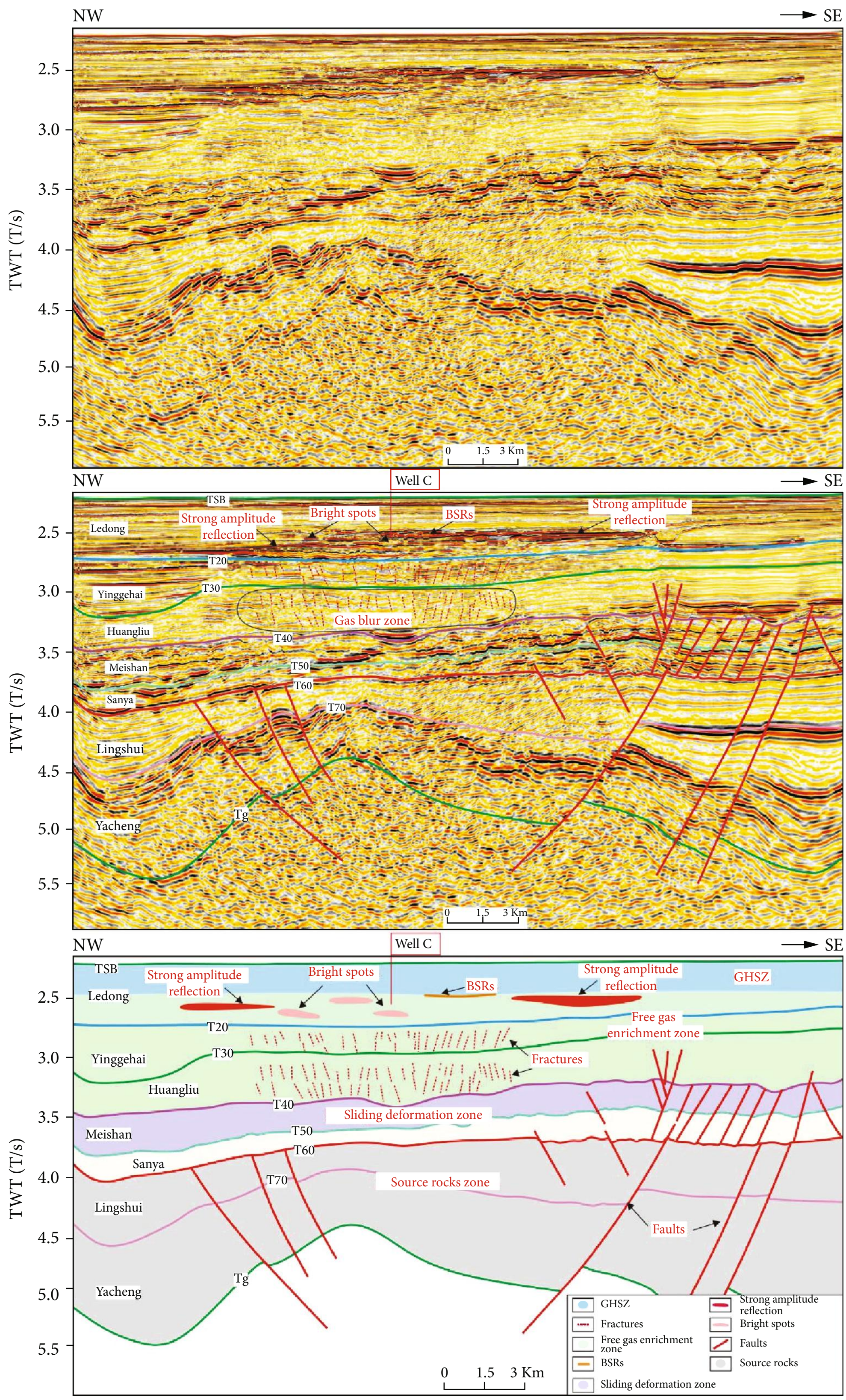
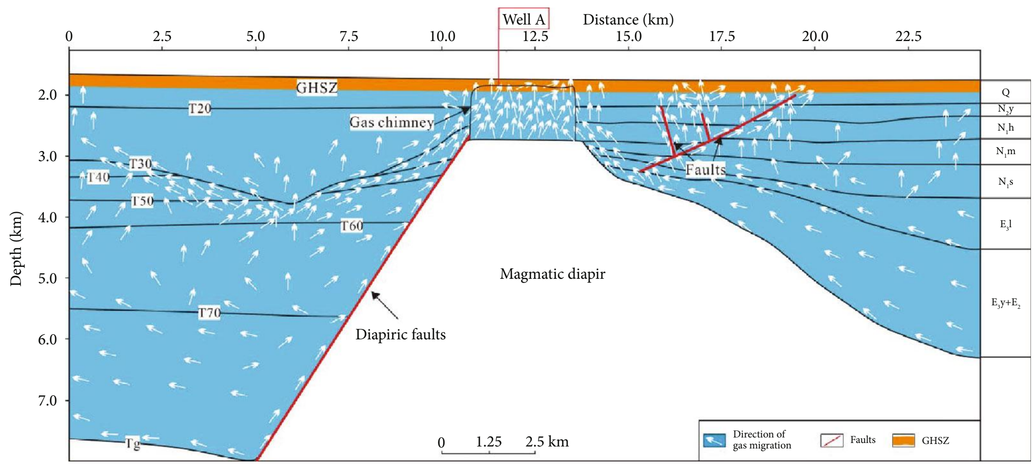
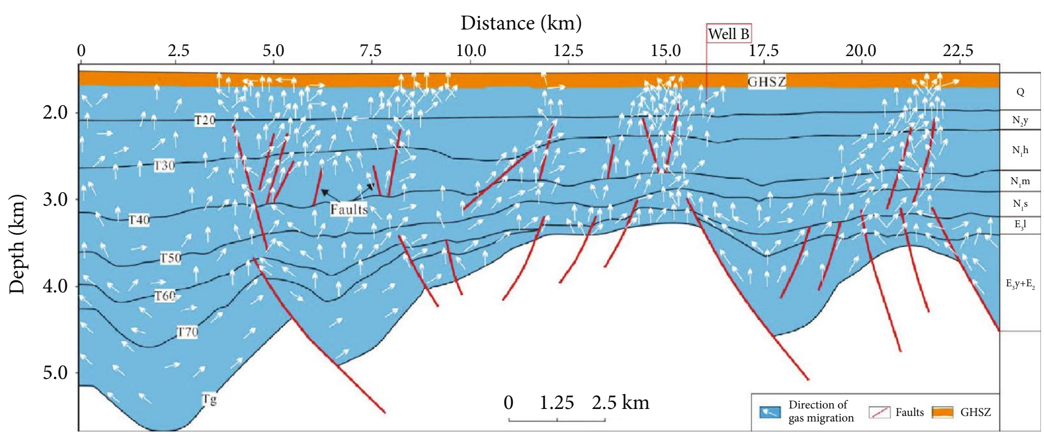


FIGURE 5: Faults and fracture system shown in the seismic profile of line 3 in the QDNB (profile location is shown in Figure 1).

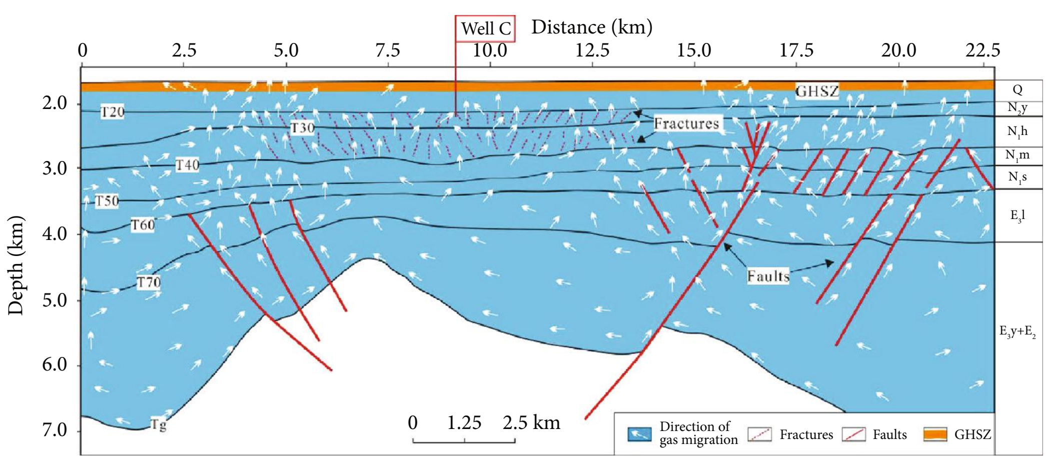
accumulation space. In addition, fractures also play a role in oil and gas migration. As shown in Figure 6(c), natural gas migrates a certain distance along with the deep faults, then continues to migrate along with the shallow small faults and fracture systems in a dispersed manner. The gas accumulations are controlled by small faults and fracture systems



(a)



(b)



(c)

Figure 6: Natural gas migration simulation profiles of lines 1, 2, and 3 in the deep-water area of the QDNB.

that present the characteristics of "wide but sparse" and are discontinuous in the vertical direction (Figure 6(c)). Compared with gas chimneys and deep faults, fracture systems are likely to have lower migration efficiency.

4.3. Characteristics of the Logging Curves. Generally, the gas hydrate-bearing layers were characterized by high resistivity (RT) and high velocity. The resistivity and acoustic (AC) curves deviated from the normal trend in well A, indicating the existence of gas hydrate deposits. According to the drilling results, three sets of gas hydrate-bearing layers were recognized in well A. In the upper and intermediate hydrate layers, from 26-50 mbsf (24 m thick) and 59-62 mbsf (13 m thick), the RT curve showed elevated characteristics with a maximum value of 5.9 Ω·m and the AC decreasing to the minimum value of 180 us/ft (Figure 7(a)). In the lower gas

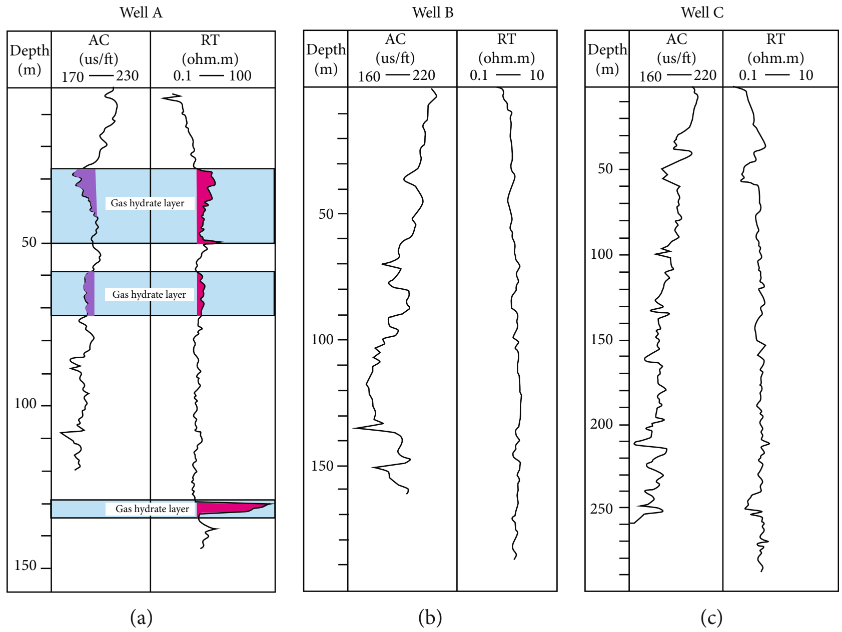


Figure 7: Logging curves of well A (a), well B (b), and well C (c) in the QDNB.

hydrate layer, no effective AC logs were obtained, but the RT curve shows obvious enhancement (Figure 7(a)), indicating that there are a lot of hydrates in this layer. However, no hydrate layers were drilled in well B and well C, and the raw log data of the RT and AC curves have no distinct indications of their trends. The AC curves showed a normal increasing trend with the depth, while the change of the resistivity curve was not significant with the mean value of 1.5 Ω·m and 1.2 Ω·m, respectively (Figures 7(b) and 7(c)).

5. Discussion

5.1. Distribution of the Natural Gas Migration Pathways. The seismic interpretation results show that the distribution of different migration pathways in the basin has certain regional variations. The diapir structures and gas chimneys were well developed in the western deep-water area of the basin, while in the eastern part of the basin, especially in Baodao and Changchang sags, faults are widely developed (Figure 8).

Gas chimneys are suggested to act as a major pathway for fluid migration from the intermediate gas reservoir to shallow sediment above the BSRs [65]. From the magmatic intrusions identified in seismic profiles, there are differences in scale and intrusion period of these diapirs across the area. The intensity of magmatic diapirism is greater in the west of the basin than in the east. A large volume of magma was intruded along deep faults, leading to the formation of low uplift and a series of secondary fault steps in the central depression zone (Figure 9). Magmatic diapirs and gas chimneys are the most widespread type of fluid migration structures in the low salient areas in the southwest of the Central depression [66]. Magmatic diapirs and gas chimneys are relatively concentrated in the deep-water area. Most of them distribute in the Ledong and Lingshui sags and Songnan and Lingnan low salient zones [11, 17, 67]. It is seen from the seismic profile that there is more faulting in the east than in the west, especially below surface boundary T60. Since the Neogene, the faults usually terminated at the T40 interface and connected the deep strata below T60, with high fault density and over a large area (Figure 10). In addition, there are a series of normal faults developed in the Baodao and Changchang depressions and the Lingnan Low Uplift area, and the southern uplift area also developed some normal faults in the Ledong Formation [37, 68, 69]. It is believed that the Neogene deep normal faults are the main migration pathways in the Baodao and Changchang Sags in the eastern area of the basin. Fractures, however, are commonly developed in the whole basin and banding distribution or associated with diapirs and faults [20, 70].

5.2. The Source of Natural Gas Forming Hydrates. The thermogenic gas generated from the deep source rocks and the microbiological gas generated from the shallow organic matter can provide natural gas for hydrate accumulation. Previous studies revealed that the natural gas composition for hydrate was biogenic gas, thermogenic gas, and mixed biogenic-thermogenic gas [11, 28, 41, 71, 72]. Methane and C_{2+} hydrocarbon were dominant in the hydrate-related gas component. According to the $C_1/(C_2 + C_3)$ value to distinguish the origin of natural gas, the biogenic gas is methane-dominated with a very high dry coefficient, and $C_1/(C_2 + C_3) > 1000$, while the thermogenic gas usually has a large amount of C_{2+} hydrocarbons and $C_1/(C_2 + C_3) <$ 100 [73–75]. In addition, it is accepted that the values of the CH_4 less than −55‰ indicate microbial origin, while the values more than −50‰ generally represent their thermogenic origin [11, 28, 73]. Accordingly, in this study area's well A, hydrate-decomposed gas has $C_1/(C_2 + C_3)$ of 20 to 200, the isotope of methane of -70‰ to -50‰, and $\delta^{13}C_2$ of -32‰ to -24‰, indicating a mixed biogenic-thermogenic gas source and mainly coal-type gas

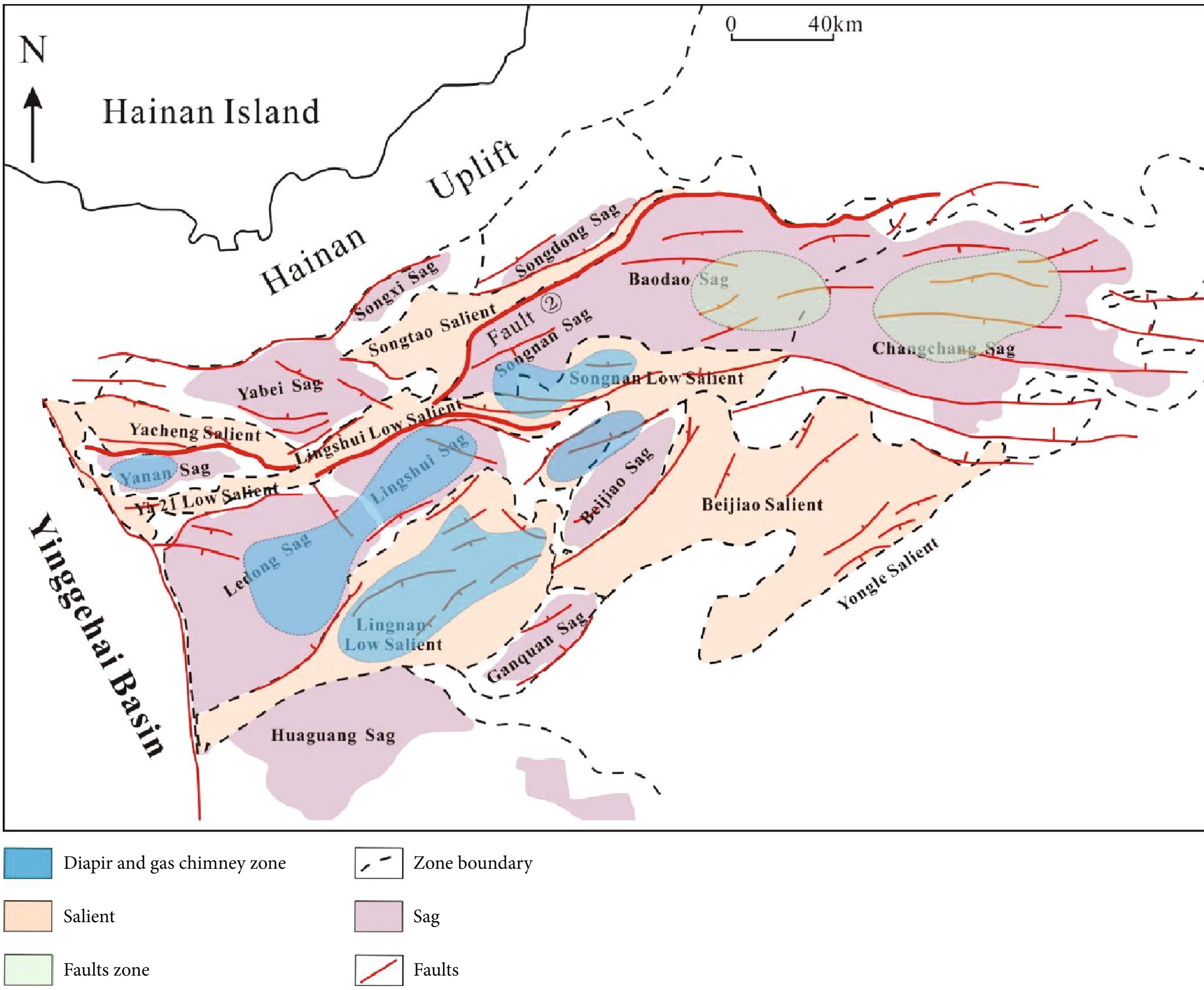


Figure 8: Distribution of the diapirs, gas chimneys, and fault structures in the QDNB (modified from [37, 59]).

(Figure 11). Previous studies showed that the BD 13-1 field, the BD 19-2 field, and the YC 13-1 field all have a thermogenic gas origin, sourcing from deeply buried coaly type gas pools and they preliminarily concluded that the C_{2+} hydrocarbon gases (thermogenic gas) within the hydrate-related gas from site GMGS5-W08 predominantly originated from deeply buried coaly type gas pools (Figure 11), while the methane has a mixed thermogenic and microbial origin [28]. In addition, Xu et al. (2021) analyzed some wells (Well-b and Well-c) in the study area and found that the hydrate decomposition gas samples were mainly within the thermogenic gas and mixed thermogenic and biogenic gas range [18] (Figure 11). Therefore, well A's gas source analysis results in the study area are completely consistent with previous research. Furthermore, researches show that in the QDNB, the biogenic gas in the hydrates was derived from the Marine source rocks deposited in the Huangliu formation and their overlying strata, and the thermogenic gas may have come from the coaly type gas pools or source rocks developed in the deep Yacheng and Lingtou formations in the Paleogene [11, 30, 41, 75, 76]. Therefore, hydrate-related gas in the shallow strata has a close relationship with the deep petroleum reservoirs in the QDNB [11].

5.3. The Efficiency of Natural Gas Migration. The migration pathways identified here, namely gas chimneys above diapirs, faults, and fracture systems, have different migration efficiencies in the basin [4].

5.3.1. Gas Chimney. Gas chimneys are widely developed in the basinal area, suggesting a viable migration pathway for gas-bearing fluids. In the seismic profile, there are many bright spots on the top of the gas chimney with strong amplitude and continuous BSR distribution with a wide range (Figure 3). Besides, according to the numerical simulation results, many gases migrated from the deep to the shallow layer along with the gas chimney (Figure 6(a)). The GHSZ in the basin models correlates well with the BSR locations in the seismic profile of line 1 (Figure 3). Furthermore, three sets of gas hydrate-bearing sections were identified in

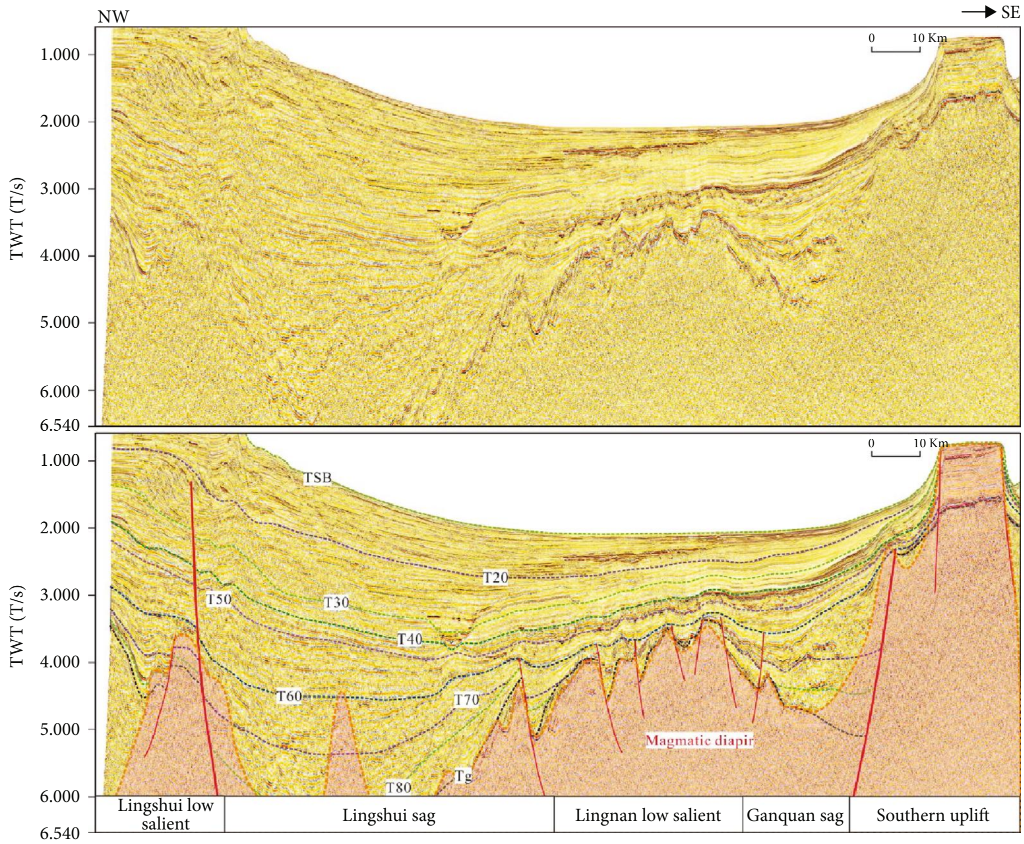


Figure 9: Seismic profile showing the characteristics of the Paleogene magmatism in Western QDNB (profile location of line 4 is shown in Figure 1).

well A with approximately 40 m thickness. All of this shows that chimneys effectively connect the deep natural gas source to shallow traps or submarine GHSZ [17, 77, 78]. The gas migrates upward through the gas chimney to the GHSZ, where it forms gas hydrates. The important natural gas pathway motivated the migration of deep thermogenic gas upward to the shallow layers. However, the distribution of diapirs in the Neogene is limited with their intrusion to shallow layers, and their effects on large-scale upward migration of oil and gas are limited, so small faults and fractures developed in the upper of the diapirs are used to migrate the gas further into the shallows.

5.3.2. Fault Structure. The formation and evolution of faults play important roles in the petroleum migration process [79, 80], as they can connect source rock and trap as "a bridge and link" [58, 81, 82]. Since the Baodao-Changchang area with relatively developed faults has not been drilled, we selected the profile with relatively developed faults in Lingnan low salient to research (the profile of line 2). In the seismic profile, there are many bright spots on the top and around the faults, especially in the area where there are many faults in the NW of the profile, and the distribution of bright spots and BSRs is larger (Figure 4). The gas migration channels shown on profile line 2 correspond with the bright spots in the seismic profile, suggesting that the fault structures are also an important natural gas migration pathway, and the deep faults control the distribution of bright spots in shallow layers. In addition, the simulation results show that oil and gas can migrate efficiently and over long distances through faults (Figure 6(b)). The drilling results of Well B showed that no hydrate was encountered, which is presumed to be due to fewer faults development at the drilling location, making it more difficult for gas to migrate to the GHSZ. The long-term activity of deep faults cut down to deep, mature source rocks facilitates oil and gas movement to shallow reservoirs over geological time. In some cases, oil and gas can migrate to the surface (e.g., the seafloor). Therefore, the combination of deep and shallow faults is essential for forming integrated migration channels to the surface or near-surface. The fault structures are characterized by high efficient, long-distance transportation of fluids.

5.3.3. Fracture System. Fractures and microcracks have been proposed as effective pathways for natural gas and oil in the QDNB [20, 83, 84]. In addition, overpressure occurred in the basin [31, 85]. When overpressure exists in the lower strata, numerous microfractures have the potential to form in the upper strata. So, the episodic opening activities of the fractures would not only constitute the main channel for energy release in an overpressured system but also form vertical fluid migration pathways [31, 86]. On the one hand, a large number of primary joints and contraction joints were developed during the process of magma condensation of intrusive

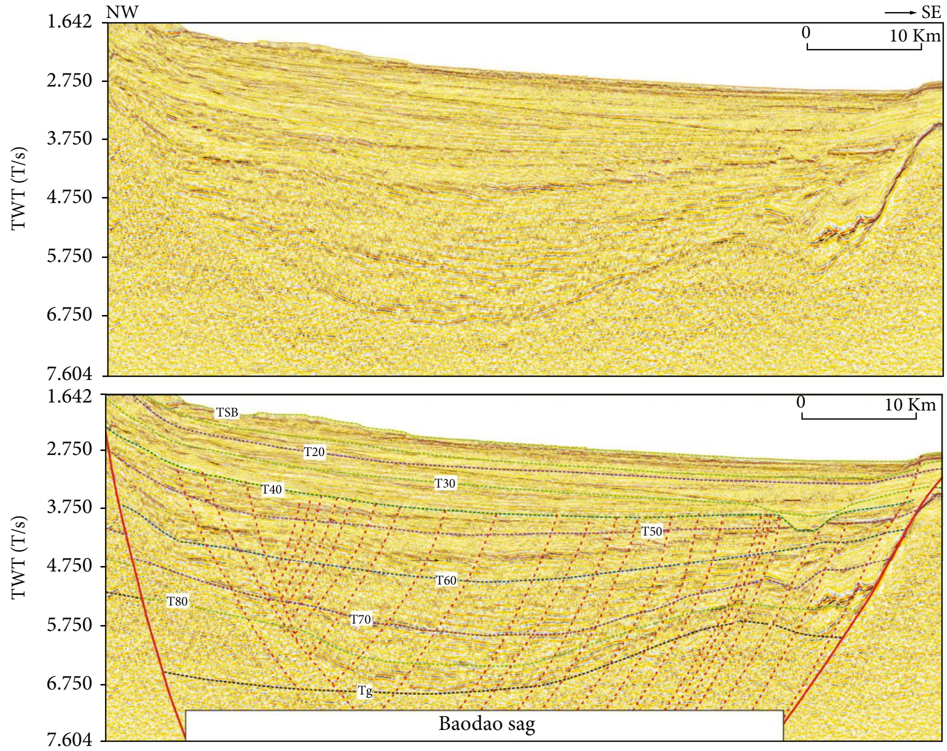


FIGURE 10: Seismic profile showing the characteristics of the Paleogene and Neogene faults in Eastern QDNB (profile location of line 5 is shown in Figure 1).

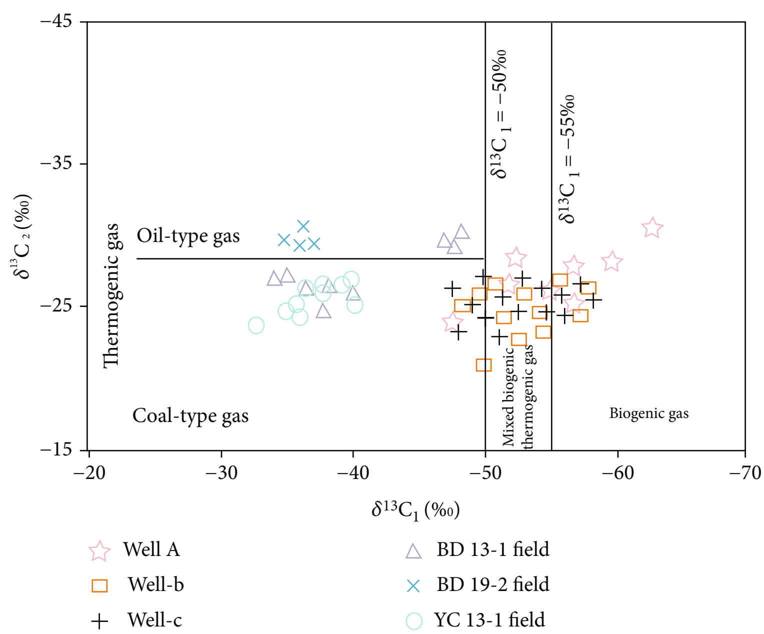


FIGURE 11: Cross-plot of $\delta^{13}C_1$ and $\delta^{13}C_2$ values for the gas samples collected from the QDNB (the $\delta^{13}C$ values of natural gas from BD13-1, BD19-2 gas fields are cited from [28], the $\delta^{13}C$ values of natural gas from YC13-1 is cited from [41], the $\delta^{13}C$ values of natural gas from well-b, well-c are cited from [18]).

rocks, and the long-term weathering and leaching of granite led to the development of stratigraphic fractures [86]. On the other hand, polygonal faults were widely developed in the upper part of the Miocene Meishan Formation, the lower part of the Huangliu Formation, and between the Pliocene Yinggehai Formation and the Pleistocene Ledong Formation in the QDNB [87–89]. Polygonal faults are believed to play an important role in oil and gas migration and accumulation

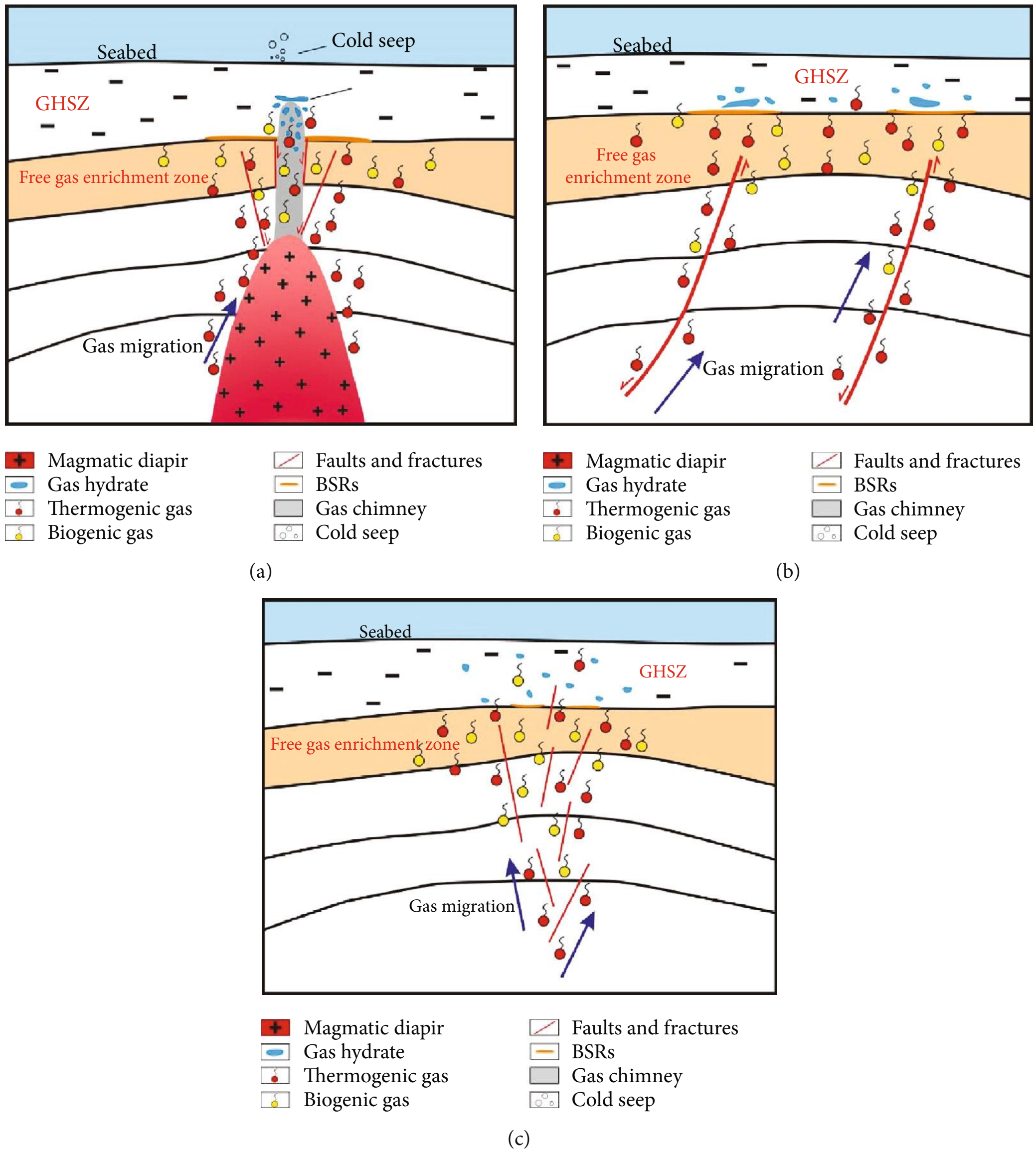


Figure 12: Hydrate enrichment models controlled by different migration pathways: (a) gas chimney; (b) fault structure; and (c) fracture system.

during the postrift thermal subsidence period in the study area [88, 90]. In addition, studies indicate that the intense tectonic activity controls the nature, occurrence, and scale of fractures that develop in the buried hill [59, 91]. Due to the tectonic deformation, a fracture network with high-angle shear fractures and tensile shear fractures almost parallel to the edge of the Magmatic diapir was developed near the contact surface between the diapir and surrounding rocks [92, 93].

In this study, the numerical simulation results show great correspondence with the bright spots on the seismic profile, indicating that the fracture system played a role in upward gas migration from depth. Gas hydrate samples have not been found in well C, indicating that fractures poorly affect oil and gas migration. Many basement faults terminate below the T60 surface, which can migrate the gas and oil to intermediate and shallow layers. So, the fracture system above surface T40 is usually regarded as a relay pathway to continue upward migration to the GHSZe and formation of the gas hydrates. The fracture system has a short transportation distance and is usually combined with other migration pathways like fault structures and magmatic diapirs to be regionally effective.

5.4. The Influence of Different Migration Pathways on Hydrate Enrichment. We suggest here that the distribution of natural gas hydrate is closely related to deep structures, especially faulting and diapirs, along with fracture systems and gas chimneys at shallower depths. Deep faults correlate with the distribution of shallow bright spots and hydrate accumulation areas, but the influence of different migration pathways on hydrate enrichment differs [4]. Based on this, three hydrate enrichment models controlled by gas chimneys, fault structures, and fracture systems are proposed in this paper (Figure 12).

It has been documented that abundant gas has been generated in the QDNB, with both microbial and thermogenic origins [57, 92]. The presence of hydrate in the QDNB is closely related to the diapiric structures, deep faults, and fracture systems. Gas chimneys often connect the deep and shallow strata, providing pathways for the deep thermogenic gas to migrate to the shallow GHSZ, and correlate with high-abundance and high-saturation hydrate reservoirs [4, 94]. Some large faults extend from depth to the shallow strata, producing favorable vertical migration channels and high migrating ability within the basin. Therefore, the deep-sourced thermogenic gas migrated vertically through the faults to the shallow area, forming high-abundance hydrate resources [78, 94]. Furthermore, fractures make up the favorable conduits and channels for continuous gas supply to the shallow section [95]. Although the migration efficiency of the fracture systems is lower than gas chimneys and fault structures, it usually develops along with the shallow small faults, leading to a relatively short distance of oil and gas migration or merely in situ accumulation. Therefore, the distribution of gas hydrate controlled by the fracture systems is scattered, and the large-scale, contiguous hydrate deposits are hardly formed by this mechanism alone.

Currently, drilling is mainly concentrated in the areas where diapirs and gas chimneys developed, and the results show that magmatic diapirs and gas chimneys control the distribution of hydrates. Baodao and Changchang sags are where fault development has not been drilled. However, the study shows that the faults in this area also impact hydrate enrichment; therefore, this area may be a favorable area for future hydrate exploration.

6. Conclusions

This study proposes three main gas migration pathways in the QDNB, SCS, namely gas chimneys, fault structures, and fracture systems. The gas chimneys appear as a vertical feature on seismic, often thicker at the base and narrowing towards the top, with fuzzy bands or wiped-out reflectors. Bright spots are generally observed on top of the gas chimneys. Fault structures show obvious stratigraphic breaks on the seismic profile, with blank reflections and bright points seen at the end of, and adjacent to, the fault. The fracture system is in the form of dendrites and flowers on the seismic profile, it is characterized by steep angles, small fault distance, and blank reflections, and it is not easy to identify.

The diverse influences of the three migration pathways on natural gas migration and hydrate enrichment are as follows: (1) The gas chimney migration pathway is characterized by continuous vertical gas distribution, sufficient gas supply, and high migration efficiency, and it makes a significant contribution to hydrate enrichment. (2) The characteristics of deep faults are high efficiency and long distance, and it also has a significant influence on hydrate enrichment. (3) Compared with the other two migration pathways mentioned above, the fracture systems have low migration efficiency and make less contribution to hydrate formation, and hence, it is not conducive to the formation of widely distributed and high-saturation gas hydrate.

The natural gas hydrates in the QDNB are mainly correlated with diapir structures, gas chimneys, and deep faults and scattered around the fracture systems. The gas chimney is the main gas hydrates migration pathway in the Ledong - Lingshui sags and Lingnan - Songnan low salient in the central depression zone, while in the Baodao and Changchang sags, the deep faults play an important role in natural gas migrating and hydrates enrichment.

Data Availability

The basin numerical simulation data used to support the findings of this study are included in the article. Previously researched data were used to support this study. These previous studies (and datasets) are cited at relevant places within the text as references [47, 50–52].

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

The cores, well data, 2D seismic lines, and 3D seismic cubes provided by Guangzhou Marine Geological Survey are much appreciated. This study was jointly supported by the Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (GML2019ZD0102), China Geological Survey Project for South China Sea Gas Hydrate Resource Exploration (No. DD20190217), and Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan) (No. CUG200608).

References

[1] E. D. Sloan, "Clathrate hydrates: the other common solid water phase," *Industrial and Engineering Chemistry Research*, vol. 39, no. 9, pp. 3123–3129, 2000.

[2] J. Q. Liang, H. B. Wang, X. Su et al., "Natural gas hydrate formation conditions and the associated controlling factors in the northern slope of the South China Sea," *Natural Gas Industry*, vol. 34, no. 7, pp. 128–135, 2014.

[3] C. F. Li, G. W. Hu, W. Zhang et al., "Influence of foraminifera on formation and occurrence characteristics of natural gas hydrates in fine-grained sediments from Shenhu area, South China Sea," *Science China Earth Science*, vol. 59, no. 11, pp. 2223–2230, 2016.

[4] M. Su, Z. B. Sha, C. M. Zhang et al., "Types, characteristics and significances of migrating pathways of gas-bearing fluids in the Shenhu area, northern continental slope of the South China Sea," *Acta Geologica Sinica-English Edition*, vol. 91, no. 1, pp. 219–231, 2017.

[5] W. Zhang, J. Q. Liang, J. A. Lu et al., "Accumulation features and mechanisms of high saturation natural gas hydrate in Shenhu Area, northern South China Sea," *Petroleum Exploration and Development*, vol. 44, no. 5, pp. 708–719, 2017.

[6] Z. Su, Y. C. Cao, R. Yang, N. Y. Wu, S. X. Yang, and H. B. Wang, "Analytical research on evolution of methane hydrate deposits at Shenhu area, northern South China Sea," *Chinese Journal of Geophysics*, vol. 55, no. 5, pp. 1764–1774, 2012.

[7] P. B. Su, J. Q. Liang, S. Y. Fu, W. J. Lv, and Y. H. Gong, "Geological background and accumulation models of gas hydrate reservoir in northern South China Sea," *Geology in China*, vol. 44, no. 3, pp. 415–427, 2017.

[8] D. F. He, W. Z. Zhao, Z. Y. Lei, H. Qu, and Y. L. Chi, "Characteristics of composite petroleum systems of superimposed basins in China," *Earth Science Frontiers*, vol. 7, no. 3, pp. 23–37, 2000.

[9] L. B. Magoon and W. Dow, "Petroleum system-from source rock to trap," *American Association of Petroleum Geologists*, vol. 14, no. 3, pp. 627–627, 1991.

[10] Q. Sun, S. Wu, J. Cartwright, and D. Dong, "Shallow gas and focused fluid flow systems in the Pearl River Mouth Basin, northern South China Sea," *Marine Geology*, vol. 44, no. 5, pp. 708–719, 2017.

[11] J. Q. Liang, W. Zhang, J. A. Lu, J. Wei, Z. Kuang, and Y. He, "Geological occurrence and accumulation mechanism of natural gas hydrates in the eastern Qiongdongnan Basin of the South China Sea: Insights from site GMGS5-W9-2018," *Marine Geology*, vol. 418, article 106042, 2019.

[12] D. G. Yoo, N. K. Kang, Y. B. Yi et al., "Occurrence and seismic characteristics of gas hydrate in the Ulleung Basin, East Sea," *Marine and Petroleum Geology*, vol. 47, no. 2013, pp. 236–247, 2013.

[13] M. G. Rowan, M. P. Jackson, and B. D. Trudgill, "Salt-related fault families and fault welds in the northern Gulf of Mexico," *AAPG Bulletin*, vol. 83, no. 9, pp. 1454–1484, 1999.

[14] W. S. Borowski, "A review of methane and gas hydrates in the dynamic, stratified system of the Blake Ridge region, offshore southeastern North America," *Chemical Geology*, vol. 205, no. 3-4, pp. 311–346, 2004.

[15] A. F. M. Freire, R. Matsumoto, and L. A. Santos, "Structural-stratigraphic control on the Umitaka Spur gas hydrates of Joetsu Basin in the eastern margin of Japan Sea," *Marine and Petroleum Geology*, vol. 28, no. 10, pp. 1967–1978, 2011.

[16] H. B. Wang, S. X. Yang, N. Y. Wu, G. X. Zhang, J. Q. Liang, and D. F. Chen, "Controlling factors for gas hydrate occurrence in Shenhu area on the northern slope of the South China Sea," *Science China Earth Science*, vol. 56, no. 4, pp. 513–520, 2013.

[17] W. Zhang, J. Q. Liang, X. L. Yang, P. B. Su, and Z. F. Wan, "The formation mechanism of mud diapirs and gas chimneys and their relationship with natural gas hydrates: insights from the deep-water area of Qiongdongnan Basin, northern South China Sea," *International Geology Review*, vol. 62, no. 7-8, pp. 789–810, 2020.

[18] L. T. Xu, Y. L. He, W. Z. Shi et al., "Main controlling factors and patterns of gas hydrate accumulation in the deep water area of Qiongdongnan Basin," *Acta Petrolei Sinica*, vol. 42, no. 5, pp. 598–610, 2021.

[19] P. B. Su, S. H. Qiao, S. Y. Fu et al., "Numerical simulation of gas hydrate accumulation in Qiongdongnan Basin, northern South China Sea," *Natural Gas Geoscience*, vol. 25, no. 7, pp. 1111–1117, 2014.

[20] W. Deng, J. Q. Liang, W. Zhang, Z. G. Kuang, T. Zhong, and Y. L. He, "Typical characteristics of fracture-filling hydrate-charged reservoirs caused by heterogeneous fluid flow in the Qiongdongnan Basin, northern south China sea," *Marine and Petroleum Geology*, vol. 124, article 104810, 2021.

[21] G. J. Crutchley, D. R. A. Fraser, I. A. Pecher, A. R. Gorman, G. Maslen, and S. A. Henrys, "Gas migration into gas hydrate-bearing sediments on the southern Hikurangi margin of New Zealand," *Journal of Geophysical Research: Solid Earth*, vol. 120, no. 2, pp. 725–743, 2015.

[22] K. F. Kroeger, A. Plaza-Faverola, P. M. Barnes, and I. A. Pecher, "Thermal evolution of the New Zealand Hikurangi subduction margin: impact on natural gas generation and methane hydrate formation - a model study," *Marine and Petroleum Geology*, vol. 63, pp. 97–114, 2015.

[23] T. Fujii, T. T. Aung, N. Wada et al., "Modeling gas hydrate petroleum systems of the Pleistocene turbiditic sedimentary sequences of the Daini-Atsumi area, eastern Nankai trough, Japan," *Interpretation*, vol. 4, no. 1, pp. SA95–SA111, 2016.

[24] K. F. Kroeger, G. J. Crutchley, M. G. Hill, and I. A. Pecher, "Potential for gas hydrate formation at the northwest New Zealand shelf margin - new insights from seismic reflection data and petroleum systems modelling," *Marine and Petroleum Geology*, vol. 83, pp. 215–230, 2017.

[25] Z. F. M. Burton, K. F. Kroeger, A. H. Scheirer, Y. Seol, B. Burgreen-Chan, and S. A. Graham, "Tectonic uplift destabilizes subsea gas hydrate: a model example from Hikurangi margin, New Zealand," *Geophysical Research Letters*, vol. 47, no. 7, pp. 1–10, 2020.

[26] Y. B. Sun, S. G. Wu, D. D. Dong, T. Lüdmann, and Y. H. Gong, "Gas hydrates associated with gas chimneys in fine-grained sediments of the northern South China Sea," *Marine Geology*, vol. 311, pp. 32–40, 2012.

[27] J. P. Jin, X. J. Wang, Y. Q. Guo et al., "Geological controls on the occurrence of recently formed highly concentrated gas hydrate accumulations in the Shenhu area, South China Sea," *Marine and Petroleum Geology*, vol. 116, article 104294, 2020.

[28] H. F. Lai, Y. X. Fang, Z. G. Kuang et al., "Geochemistry, origin and accumulation of natural gas hydrates in the Qiongdongnan Basin, South China Sea: implications from site GMGS5-W08," *Marine and Petroleum Geology*, vol. 123, article 104774, 2021.

[29] D. D. Wang, G. Q. Dong, G. Z. Zhang, Z. X. Li, Q. Mao, and G. Z. Song, "Coal seam development characteristics and distribution predictions in marginal sea basins: Oligocene Yacheng Formation coal measures, Qiongdongnan Basin, northern region of the South China Sea," *Australian Journal of Earth Sciences*, vol. 67, no. 3, pp. 393–409, 2020.

[30] W. L. Zhu, B. J. Huang, L. J. Mi, R. W. T. Wilkins, N. Fu, and X. M. Xaio, "Geochemistry, origin, and deep-water exploration potential of natural gases in the Pearl River Mouth and Qiongdongnan Basin, South China Sea," *AAPG Bulletin*, vol. 93, no. 6, pp. 741–761, 2009.

[31] W. Z. Shi, Y. H. Xie, Z. F. Wang, X. S. Li, and C. X. Tong, "Characteristics of overpressure distribution and its implication for hydrocarbon exploration in the Qiongdongnan Basin," *Journal of Asian Earth Sciences*, vol. 66, pp. 150–165, 2013.

[32] G. Song, H. Wang, H. Gan et al., "Paleogene tectonic evolution controls on sequence stratigraphic patterns in the central part of deepwater area of Qiongdongnan Basin, Northern South China Sea," *Journal of Earth Science*, vol. 25, no. 2, pp. 275–288, 2014.

[33] J. X. He, W. H. Wu, Y. H. Zhu, S. H. Chen, S. S. Cui, and X. F. Gong, "Genetic types, migration and accumulation of oil & gas and exploration proposal in north marginal basin, South China Sea," *Natural Gas Geoscience*, vol. 21, no. 1, pp. 7–17, 2010.

[34] J. X. Chen, Y. X. Guan, H. B. Song et al., "Distribution characteristics and geological implications of pockmarks and mud volcanoes in the northern and western continental margins of the South China Sea," *Chinese Journal of Geophysics*, vol. 58, no. 3, pp. 919–938, 2015.

[35] Q. L. Sun, S. G. Wu, G. S. Yao, and F. L. Lue, "Characteristics and formation mechanism of polygonal faults in Qiongdongnan Basin, Northern South China Sea," *Journal of Earth Science*, vol. 20, no. 1, pp. 180–192, 2009.

[36] C. Lei, J. Y. Ren, J. X. Pei, H. T. Lin, X. Y. Yin, and D. J. Tong, "Tectonic framework and multiple episode tectonic evolution in deep-water area of Qiongdongnan Basin, Northern Continental Margin of South China Sea," *Earth Science*, vol. 36, no. 1, pp. 151–162, 2011.

[37] C. Zhang, Z. Wang, Z. Sun, Z. Sun, J. Liu, and Z. Wang, "Structural differences between the western and eastern Qiongdongnan Basin: evidence of Indochina block extrusion and South China Sea seafloor spreading," *Marine Geophysical Research*, vol. 34, no. 3-4, pp. 309–323, 2013.

[38] B. Hu, L. S. Wang, W. B. Yan et al., "The tectonic evolution of the Qiongdongnan Basin in the northern margin of the South China Sea," *Journal of Asian Earth Sciences*, vol. 77, pp. 163–182, 2013.

[39] R. Wang, W. Z. Shi, X. Y. Xie et al., "Clay mineral content, type, and their effects on pore throat structure and reservoir properties: Insight from the Permian tight sandstones in the Hangjinqi area, north Ordos Basin, China," *Marine and Petroleum Geology*, vol. 115, article 104281, 2020.

[40] K. N. Mao, X. N. Xie, Y. H. Xie, J. Y. Ren, and H. Chen, "Postrift tectonic reactivation and its effect on deep-water deposits in the Qiongdongnan Basin, northwestern South China Sea," *Marine Geophysical Research*, vol. 36, no. 2-3, pp. 227–242, 2015.

[41] B. J. Huang, X. M. Xiao, and X. X. Li, "Geochemistry and origins of natural gases in the Yinggehai and Qiongdongnan basins, offshore South China Sea," *Organic Geochemistry*, vol. 34, no. 7, pp. 1009–1025, 2003.

[42] W. H. Li, Z. H. Zhang, K. Zheng, and Y. C. Li, "Geochemical characteristics and developmental models of the Eocene source rocks in the Qiongdongnan Basin, northern South China Sea," *Energy & Fuels*, vol. 31, no. 12, pp. 13487–13493, 2017.

[43] X. D. Xu, Y. Z. Zhang, G. Liang et al., "Hydrocarbon source condition and accumulation mechanism of natural gas in deep-water area of Qiongdongnan Basin, northern South China Sea," *Natural Gas Geoscience*, vol. 27, no. 11, pp. 1985–1992, 2016.

[44] W. H. Li, Z. H. Zhang, Y. C. Li, C. Liu, and N. Fu, "The main controlling factors and developmental models of Oligocene source rocks in the Qiongdongnan Basin, northern South China Sea," *Petroleum Science*, vol. 10, no. 2, pp. 161–170, 2013.

[45] W. H. Li, Z. H. Zhang, Y. C. Li, and N. Fu, "New perspective of Miocene marine hydrocarbon source rocks in deep-water area in Qiongdongnan Basin of northern South China Sea," *Acta Oceanologica Sinica*, vol. 31, no. 5, pp. 107–114, 2012.

[46] G. C. Zhang, Y. N. Zhang, H. L. Shen, and Y. P. He, "An analysis of natural gas exploration potential in the Qiongdongnan Basin by use of the theory of "joint control of source rocks and geothermal heat"," *Natural Gas Industry B*, vol. 1, no. 1, pp. 41–50, 2014.

[47] L. T. Kong, H. H. Chen, H. W. Ping, P. Q. Zhai, Y. H. Liu, and J. Z. Zhu, "Formation pressure modeling in the Baiyun Sag, northern South China Sea: implications for petroleum exploration in deep-water areas," *Marine and Petroleum Geology*, vol. 97, pp. 154–168, 2018.

[48] L. J. Mi, Z. T. Zhang, X. Pang et al., "Main controlling factors of hydrocarbon accumulation in Baiyun Sag at northern continental margin of South China Sea," *Petroleum Exploration and Development*, vol. 45, no. 5, pp. 963–973, 2018.

[49] L. Y. Sun, X. J. Wang, M. He et al., "Thermogenic gas controls high saturation gas hydrate distribution in the Pearl River Mouth Basin: evidence from numerical modeling and seismic anomalies," *Ore Geology Reviews*, vol. 127, article 103846, 2020.

[50] M. Kong, *The analysis of overpressure and hydrocarbon migration in Qiongdongnan Basin*, China University of Geosciences (Wuhan), 2010.

[51] X. Pang, C. M. Cheng, D. J. Peng et al., "Sequence stratigraphy of deep-water fan system of Pearl River, South China Sea," *Earth Science Frontiers*, vol. 14, no. 1, pp. 220–229, 2007.

[52] W. L. Zhu, Z. J. Huang, Z. G. Tong, and Y. J. Wang, "Selection of petroleum exploration area in offshore China: in terms of the analysis of thermal simulation experiments and genetic resources assessment," *Petroleum Geology and Experiment*, vol. 30, no. 6, pp. 537–542, 2008.

[53] K. Barsoum, D. M. Martera, and N. A. Menardi, "Gas Chimneys in the nile delta slope and gas fields occurrence," in *EAGE Conference on Geology and Petroleum Geology of the Mediterranean and Circum-Mediterranean Basins*, St. Julions, Malta, 2000.

[54] K. Graue, "Mud volcanoes in deepwater Nigeria," *Marine and Petroleum Geology*, vol. 17, no. 8, pp. 959–974, 2000.

[55] L. I. Dimitrov, "Mud volcanoes–the most important pathway for degassing deeply buried sediments," *Earth-Science Reviews*, vol. 59, no. 1-4, pp. 49–76, 2002.

[56] P. B. Su, J. Q. Liang, Z. J. Zhang, and Z. B. Sha, "Analysis on bright spots and dim out of seismic section for diffusion-type hydrate in Shenhu area," *Earth Science Frontiers*, vol. 24, no. 4, pp. 51–56, 2017.

[57] M. Su, R. Yang, H. Wang et al., "Gas hydrates distribution in the Shenhu area, northern South China Sea: comparisons between the eight drilling sites with gas hydrate petroleum system," *Geologica Acta*, vol. 14, no. 2, pp. 79–100, 2016.

[58] Z. F. Wang, Z. Liu, S. Cao et al., "Vertical migration through faults and hydrocarbon accumulation patterns in deepwater areas of the Qiongdongnan Basin," *Acta Oceanologica Sinica*, vol. 33, no. 12, pp. 96–106, 2014.

[59] W. Zhang, J. Q. Liang, P. B. Su et al., "Distribution and characteristics of mud diapirs, gas chimneys, and bottom simulating reflectors associated with hydrocarbon migration and gas hydrate accumulation in the Qiongdongnan Basin, northern slope of the South China Sea," *Geological Journal*, vol. 54, no. 6, pp. 3556–3573, 2019.

[60] L. Loncke, J. Mascle, and F. S. Parties, "Mud volcanoes, gas chimneys, pockmarks and mounds in the Nile deep-sea fan (Eastern Mediterranean): geophysical evidences," *Marine and Petroleum Geology*, vol. 21, no. 6, pp. 669–689, 2004.

[61] R. Wang, W. Z. Shi, X. Y. Xie et al., "Coupling of strike-slip faulting and lacustrine basin evolution: Sequence stratigraphy, structure, and sedimentation in the North Yellow Sea Basin (West Bay basin offshore North Korea), eastern China," *Marine and Petroleum Geology*, vol. 120, article 104548, 2020.

[62] Z. X. Cai, "Paleo-structural stress field simulation for fracture prediction and its application," *Science Technology and Engineering*, vol. 13, no. 2, pp. 446–449, 2013.

[63] C. F. Tsang and I. Neretnieks, “Flow channeling in heterogeneous fractured rocks,” *Reviews of Geophysics*, vol. 36, no. 97, pp. 275–298, 1998.

[64] R. A. Nelson, *Geologic Analysis of Naturally Fractured Reservoirs*, Gulf Publishing Company, Houston, 2001.

[65] J. Ye, J. Wei, J. Liang, J. Lu, H. Lu, and W. Zhang, “Complex gas hydrate system in a gas chimney, South China Sea,” *Marine and Petroleum Geology*, vol. 104, pp. 29–39, 2019.

[66] L. J. Wang, J. T. Zhu, H. T. Zhuo et al., “Seismic characteristics and mechanism of fluid flow structures in the central depression of Qiongdongnan Basin, northern margin of South China Sea,” *International Geology Review*, vol. 62, no. 7-8, pp. 1108–1130, 2019.

[67] Y. C. Zhang, J. Gan, X. D. Xu, G. Liang, and X. Li, “The source and natural gas lateral migration accumulation model of Y8-1 gas bearing structure, east deep water in the Qiongdongnan Basin,” *Earth Science*, vol. 44, no. 8, pp. 2609–2616, 2019.

[68] X. J. Wang, T. S. Collett, M. W. Lee, S. X. Yang, Y. Q. Guo, and S. G. Wu, “Geological controls on the occurrence of gas hydrate from core, downhole log, and seismic data in the Shenhu area, South China Sea,” *Marine Geology*, vol. 357, pp. 272–292, 2014.

[69] J. Y. Ren, D. J. Zhang, D. J. Tong et al., “Characterising the nature, evolution and origin of detachment fault in central depression belt, Qiongdongnan Basin of South China Sea: evidence from seismic reflection data,” *Acta Oceanologica Sinica*, vol. 33, no. 12, pp. 118–126, 2014.

[70] M. Riedel, T. S. Collett, P. Kumar, A. V. Sathe, and A. Cook, “Seismic imaging of a fractured gas hydrate system in the Krishna-Godavari Basin offshore India,” *Marine and Petroleum Geology*, vol. 27, no. 7, pp. 1476–1493, 2010.

[71] N. Y. Wu, H. Q. Zhang, S. X. Yang et al., “Gas hydrate system of Shenhu area, northern South China Sea: geochemical results,” *Journal of Geological Research*, vol. 2011, Article ID 370298, 10 pages, 2011.

[72] Y. H. Zhu, X. Huang, S. Y. Fu, and P. B. Su, “Gas sources of natural gas hydrates in the Shenhu drilling area, South China Sea: geochemical evidence and geological analysis,” *Acta Geologica Sinica-English Edition*, vol. 87, no. 3, pp. 767–776, 2013.

[73] J. X. He, W. Yan, Y. H. Zhu et al., “Bio-genetic and sub-biogenetic gas resource potential and genetic types of natural gas hydrate in the northern marginal basins of South China Sea,” *Natural Gas Industry*, vol. 33, no. 6, pp. 121–128, 2013.

[74] A. V. Milkov, “Molecular and stable isotope compositions of natural gas hydrates: a revised global dataset and basic interpretations in the context of geological settings,” *Organic Geochemistry*, vol. 36, no. 5, pp. 681–702, 2005.

[75] B. J. Huang, X. S. Li, Z. F. Wang, L. Li, and Y. W. Huang, “Characteristics and gas generation potential of source rocks in the deepwater area, the Qiongdongnan basin,” *China Offshore Oil Gas*, vol. 24, no. 4, pp. 1–7, 2012.

[76] B. J. Huang, H. Tiam, X. S. Li, Z. F. Wang, and X. M. Xiao, “Geochemistry, origin and accumulation of natural gases in the deepwater area of the Qiongdongnan Basin, South China Sea,” *Marine and Petroleum Geology*, vol. 72, pp. 254–267, 2016.

[77] X. Xu, Z. F. Wan, X. Q. Wang, Y. F. Sun, and B. Xia, “The characteristics of heat flow in the Shenhu gas hydrate drilling area, northern South China Sea,” *Marine Geophysical Research*, vol. 37, no. 4, pp. 325–335, 2016.

[78] A. V. Milkov, “Worldwide distribution of submarine mud volcanoes and associated gas hydrates,” *Marine Geology*, vol. 167, no. 1-2, pp. 29–42, 2000.

[79] G. Fu and X. F. Fu, “Controlling of fault migration system and its combination to the formation and distribution of oil or gas reservoirs,” *Global Geology*, vol. 20, no. 4, pp. 344–349, 2001.

[80] I. Moretti, “The role of faults in hydrocarbon migration,” *Petroleum Geoscience*, vol. 4, no. 1, pp. 81–94, 1998.

[81] W. A. England, A. S. Mackenzie, O. M. Mann, and T. M. Quigley, “The movement and entrapment of petroleum fluids in the subsurface,” *Journal of the Geological Society*, vol. 144, no. 2, pp. 327–347, 1987.

[82] S. Losh, “Oil migration is a major growth fault: structural analysis of the pathfinder core, South Eugene Island Block, offshore Louisiana,” *AAPG Bulletin-American Association of Petroleum Geologists*, vol. 82, no. 9, pp. 1694–1710, 1998.

[83] J. Q. Liang, S. Y. Fu, F. Chen et al., “Submarine methane leakage and hydrate accumulation in the northeastern South China Sea,” *Natural Gas Geoscience*, vol. 28, no. 5, pp. 761–770, 2017.

[84] S. G. Wu, D. D. Dong, S. X. Yang et al., “Preliminary study on the formation model of natural gas hydrate system of fine sediments in the northern slope of the South China Sea,” *Chinese Journal of Geophysics*, vol. 52, no. 7, pp. 1849–1857, 2009.

[85] M. F. Wang, “The characteristics of overpressure and its relationship with the distribution of oil and gas, in the Qiongdongnan Basin,” *Marine Petroleum*, vol. 23, no. 1, pp. 15–22, 2003.

[86] F. Zhou, A. Q. Liu, and P. Song, “Fine description technique of vertical migration pathway in HTHP formations of Qiongdongnan Basin,” *Journal of Chongqing University of Science and Technology (Natural Sciences Edition)*, vol. 21, no. 4, pp. 23–27, 2019.

[87] X. Wang, S. Wu, S. Yuan et al., “Geophysical signatures associated with fluid flow and gas hydrate occurrence in a tectonically quiescent sequence, Qiongdongnan Basin, South China Sea,” *Geofluids*, vol. 10, no. 3, pp. 351–368, 2010.

[88] Q. L. Sun, S. G. Wu, F. L. Lue, and S. Q. Yuan, “Polygonal faults and their implications for hydrocarbon reservoirs in the southern Qiongdongnan Basin, South China Sea,” *Journal of Asian Earth Sciences*, vol. 39, no. 5, pp. 470–479, 2010.

[89] X. Pang, S. K. Yang, M. Zhu, and J. S. Li, “Deep-water fan systems and petroleum resources on the northern slope of the South China Sea,” *Acta Geologica Sinca-English Eddition*, vol. 78, no. 3, pp. 626–631, 2004.

[90] J. H. Han, J. G. Leng, and Y. M. Wang, “Characteristics and genesis of the polygonal fault system in southern slope of the Qiongdongnan Basin, South China Sea,” *Marine and Petroleum Geology*, vol. 70, pp. 163–174, 2016.

[91] L. You, S. L. Xu, X. L. Mao, J. Zhong, Y. Q. Jiao, and X. F. Xiong, “Reservoir characteristics and genetic mechanisms of the Mesozoic granite buried hills in the deep-water of the Qiongdongnan Basin, northern South China Sea,” *Acta Geologica Sinica-English Edition*, vol. 95, no. 1, pp. 259–267, 2021.

[92] J. Liu, M. J. Sun, R. Yang, M. Su, and H. Yan, “Diapir conduit fluid mechanism and its relationship with gas hydrate accumulations,” *Geoscience*, vol. 21, no. 4, pp. 1399–1407, 2016.

[93] K. M. Brown, “The nature and hydrogeologic significance of mud diapirs and diatremes for accretionary systems,” *Journal of Geophysical Research-Solid Earth and Planets*, vol. 95, no. B6, pp. 8969–8982, 1990.

[94] J. X. He, P. B. Su, Z. Q. Lu, W. Zhang, Z. J. Liu, and X. T. Li, "Prediction of gas sources of natural gas hydrate in the Qiongdongnan Basin, northern South China Sea, and its migration, accumulation and reservoir formation pattern," *Natural Gas Industry*, vol. 35, no. 8, pp. 19–29, 2015.

[95] G. G. Hui, S. Z. Li, L. L. Guo et al., "Source and accumulation of gas hydrate in the northern margin of the South China Sea," *Marine and Petroleum Geology*, vol. 69, pp. 127–145, 2016.