



# Analysis of the Thermogenic Gas Source of Natural Gas Hydrates Over the Dongsha Waters in the Northern South China Sea

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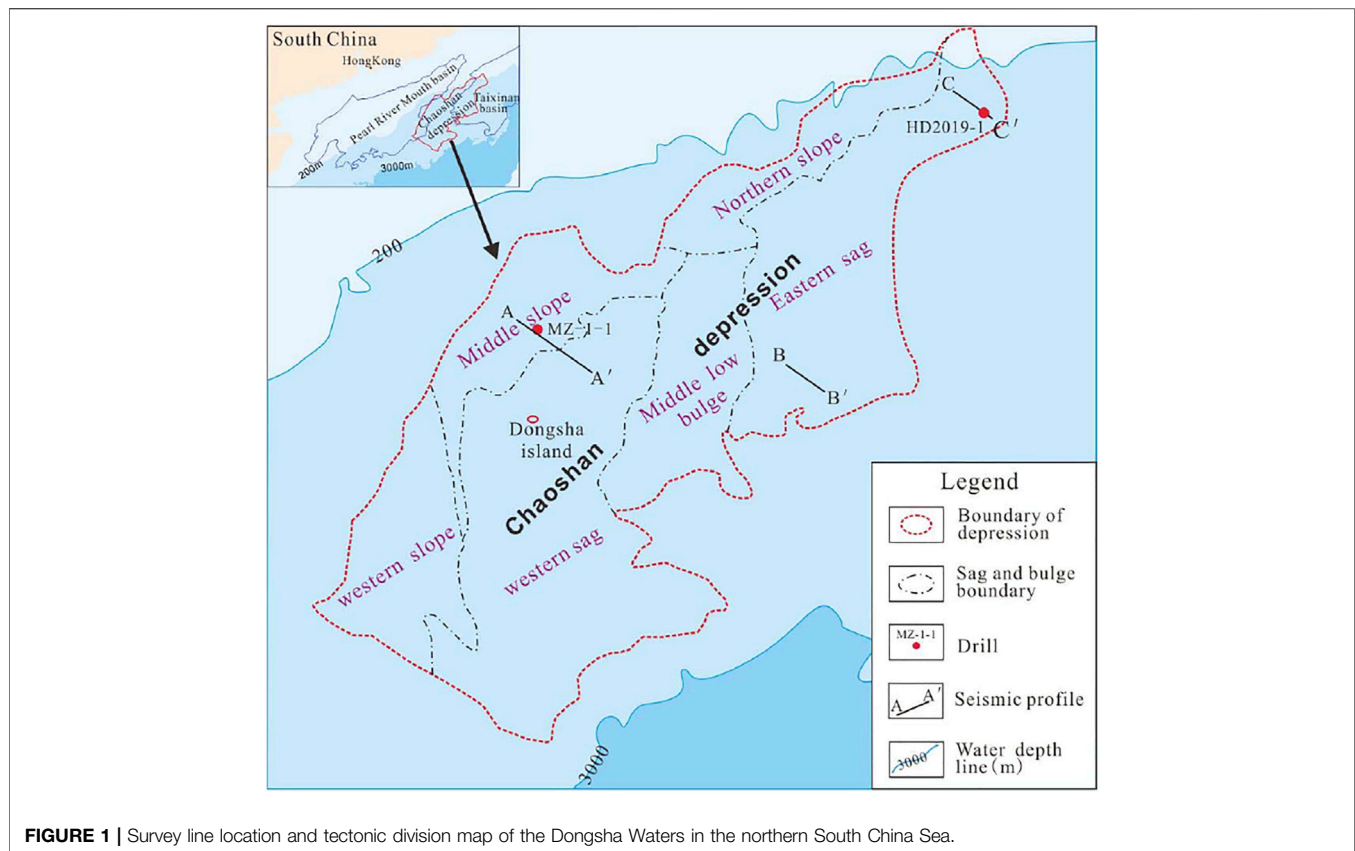
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Gas hydrates were newly discovered in the Dongsha Waters of the South China Sea by drilling in 2013 and 2019. The drilling results show that the hydrates consist of microbial gas and thermogenic gas, but the source layers of the thermogenic gas are not clear. The Chaoshan depression is the largest relict Mesozoic basin under the Dongsha Waters where thick  $T_3$ –K strata, up to 5000 m, have developed under thin Cenozoic sediments. The  $T_3$ – $J_1$  and  $J_3$  bear the two main layers of hydrocarbon source rocks rich in  $II_2$ –III type organic matter, mainly in the western sag, the middle low bulge, and the eastern sag. The  $T_3$ – $J_1$  developed bathyal - neritic mud rocks, generally greater than 400 m in thickness. The  $J_3$  mainly developed closed and semi-closed bay type mud, also  $II_2$ –III type. Nowadays these two layers are in their mature - over mature stages, thus potentially high-producing. There have developed deep faults cutting through the Mesozoic strata and distributing fractures within the Cenozoic sediments. Analysis of geochemical and geological samples dredged from the seabed indicates a significant oil and gas leakage activity well correlated spatially with the Mesozoic-associated faults. The association of fault-fractures can act as good channels for the thermogenic gas to move upward and diffuse into the temperature pressure stabilization zone of the hydrate. Thus, sufficient gas from the Mesozoic production layers is deemed the main source of thermogenic gas. The area where the Mesozoic faults are activated is the main leakage area of thermogenic gas, thus the main target for future hydrate exploration.

**Keywords:** chaoshan depression, the dongsha waters in the northern south china sea, mesozoic erathem, source of gas hydrate, gas channel by fault-fracture association

## INTRODUCTION

The northern part of the South China Sea has undergone more than 20 years of regional geological surveys. Rich hydrates have been discovered in the Shenhui and Dongsha survey areas, wholly in the Cenozoic Basins, in the northern South China Sea (Han et al., 2013; Su et al., 2014; Liang et al., 2016; Su et al., 2017; Zhang et al., 2017; Sha et al., 2019; He et al., 2020; Teng et al., 2020). Recently, hydrates (Zhong et al., 2020) have also been found in the Chaoshan depression, in a relict Mesozoic Basin in the Dongsha Waters, where the Cenozoic sequences are very thin while the Mesozoic strata is thick (Shao et al., 2007; Yang et al., 2008; Hao et al., 2009; Zhong et al., 2020). Although the hydrates found in the Dongsha Waters are similar in mixed biogenic and thermogenic compositions to the hydrates found elsewhere in the South China Sea, the



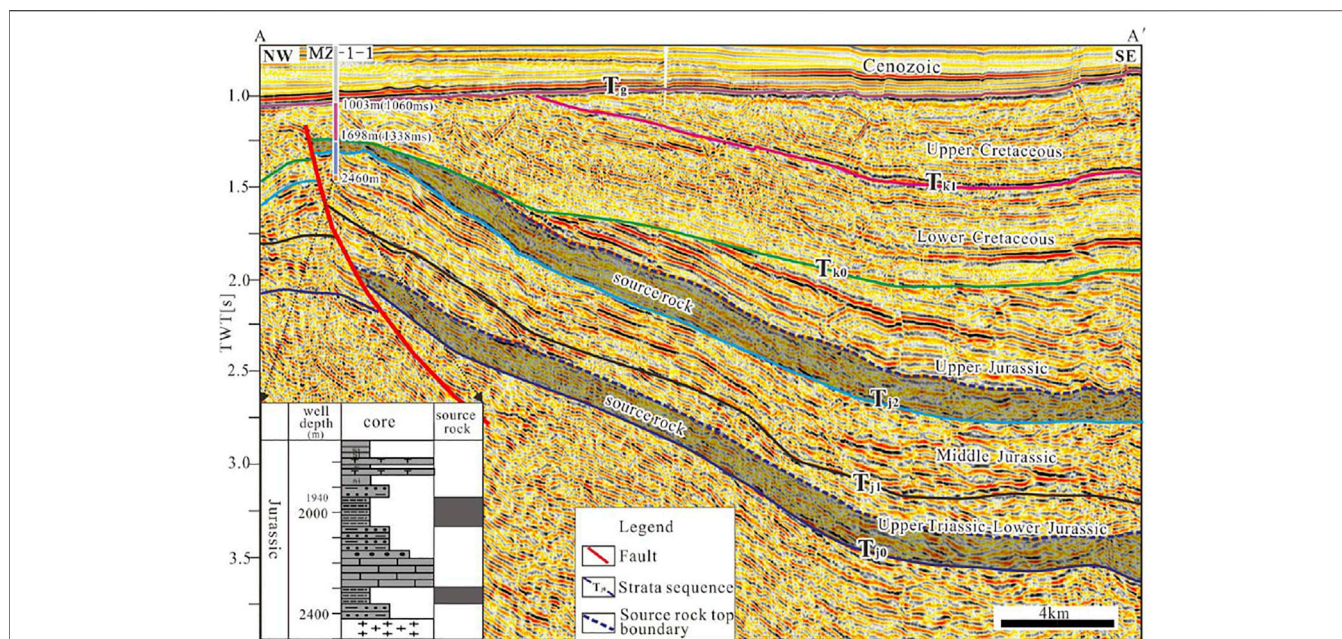
thermogenic gas in the lower part may not come from the Cenozoic layers as they are too thin (less than 1000 m) to produce enough thermogenic gas. With seismic and geochemical data, it is shown that the Mesozoic marine sedimentary layers are a potential source of the thermogenic gas. Hydrates and a high geochemical anomaly index indicate that gas seepage correlates well with the deep Mesozoic faults. Association of the deep fault in Mesozoic and shallow fracture in Cenozoic act as good transport passages. More hydrates can be expected from the Mesozoic source.

## GEOLOGICAL OVERVIEW SETTING OF THE CHAOSHAN DEPRESSION

The Chaoshan depression is a Mesozoic Basin which lies in the Dongsha Waters in the northeast of the South China Sea, with an area of more than 37,000 km<sup>2</sup>. The residual maximal thickness of Mesozoic sedimentary sequences is more than 5000 m (Zhong et al., 2020). It can be subdivided into six subordinate units, i.e., the eastern sag, the western sag, the middle low bulge, the northern slope, the middle slope, and the western slope (Figure 1). In September 2003, an exploration well (MZ-1-1) was drilled north of Dongsha Island. Although no hydrocarbon was shown, it confirmed the existence of thick Mesozoic sequences, including marine hydrocarbon source

rocks and effective reservoir-cap combinations (Shao et al., 2007; Hao et al., 2009). The Chaoshan depression developed in the upper Triassic - lower Jurassic (T<sub>3</sub>-J<sub>1</sub>), middle Jurassic (J<sub>2</sub>), upper Jurassic (J<sub>3</sub>), and Cretaceous (K) (Qiang et al., 2018; Sun et al., 2018; Zhong et al., 2020). The T<sub>3</sub>-J<sub>1</sub> is a set of neritic - bathyal depositions (Chen et al., 2005), the thickness is generally greater than 500 m, locally up to 3000 m. The J<sub>2</sub> is a set of neritic depositions, with thickness generally greater than 400 m, locally up to 1200 m. The J<sub>3</sub> is a set of neritic—bathyal depositions (Shao et al., 2007; Wu et al., 2007; Hao et al., 2009), 200–2500 m thick. The lower Cretaceous is a set of transitional facies depositions. The upper Cretaceous deposition has river-alluvial plain facies, lake facies to the north, and transitional facies to the south (Shao et al., 2007; Hao et al., 2009).

In 2013, the Guangzhou Marine Geological Survey (GMGS) conducted the first hydrate drilling exploration in the northeastern Chaoshan depression and obtained evidence of hydrates at 8 sites of the 13 drilling sites. The hydrates occur in various forms such as massive, lamellar, veined, and nodular and scattered (Zhang et al., 2015). In 2019, another well, HD 2019-1 (Figure 1), was successful again in drilling gas hydrates from 60 m below the seabed in the same area. The new sampled hydrates comprise rich thermogenic gas (Zhong et al., 2020). However, the details of the hydrates and the geology have been less reported. Given



**FIGURE 2 | (A,A')** Seismic section typical of the mud hydrocarbon source layers developed in the Chaoshan depression (see line position in **Figure 1**).

the thin Cenozoic sediments, the underlying thick Mesozoic is inferred as the potential gas source for the hydrates (Zhong et al., 2020). More than 20 years of geophysical and geochemical surveys enable analysis of the source.

## DATA AND METHODS

GMGS has conducted extensive 2D multi-channel seismic and seafloor site sampling surveys over the Dongsha Waters. Up to now, the seismic grid density of the central and western parts of the Chaoshan depression has reached 16 km × 32 km, locally 2 km × 4 km, being coarser in the northeast boundary. The most-used 2D seismic streamer has 480 channels in 12.5 m spacing. The shooting spacing is 37.5 m using a source capacity of 5080 cubic inches. The coverage is up to 80 fold. The seismic profiles displayed later have been processed with routine industry procedures and pre-stacked time migration.

The seismic data were interpreted with the GeoFrame 2012 software platform. The formation is interpreted primarily based on correlation with the geologic exploration of the MZ-1-1 well (**Figure 2**) and seismic stratigraphic analysis. On this basis, combined with the reflection characteristics of productive mudstone on the seismic profile, data were traced by section, and time-depth-thickness was converted and mapped.

With the drill-seismic correlation, a basin simulation was carried out using IES Petromod software, and the distribution plan of the source rock Ro was mapped.

Site geochemical samples were collected in the central and southwestern Chaoshan depression with a grid of 8 km × 16 km.

About 200 samples were selected for testing with items ranging from top air, top air heavy hydrocarbons, acid hydrolyzed hydrocarbons, acid hydrolyzed hydrocarbons, heavy hydrocarbons, fluorescence spectrum, altered carbonates, methane oxidizing bacteria, and butane oxidizing bacteria. The tests were carried out in Hefei Training and Testing Center of Sinopec Asset Management Co., Ltd. The indicators of the top air, top air heavy hydrocarbons, acid hydrolyzed hydrocarbons, altered carbonates, and methane oxidizing bacteria were selected and comprehensively analyzed. After normalization of these indicators, the Kriging and moving average methods were respectively used to map the comprehensive anomaly distribution of geochemical exploration.

## RESULTS

### Two Sets of Hydrocarbon Source Layers and Their Distributions

It was confirmed from the MZ-1-1 well that the Chaoshan depression had developed two sets of mainly hydrocarbon source rocks in the T<sub>3</sub>-J<sub>1</sub> and bathyal—neritic and neritic facies in the J<sub>3</sub>. The organic carbon content of the 1800–2000 m section of late Jurassic was 0.18–1.15%, the average was 0.67%, belonging to poor hydrocarbon source rock. The thickness of hydrocarbon source rock in the 2100 m–2400 m section of in the T<sub>3</sub>-J<sub>1</sub> was 46.16 m, and the organic carbon content was 1.00–1.48%, with an average of 1.32%, belonging to medium hydrocarbon source rock. These two sets of hydrocarbon source rocks

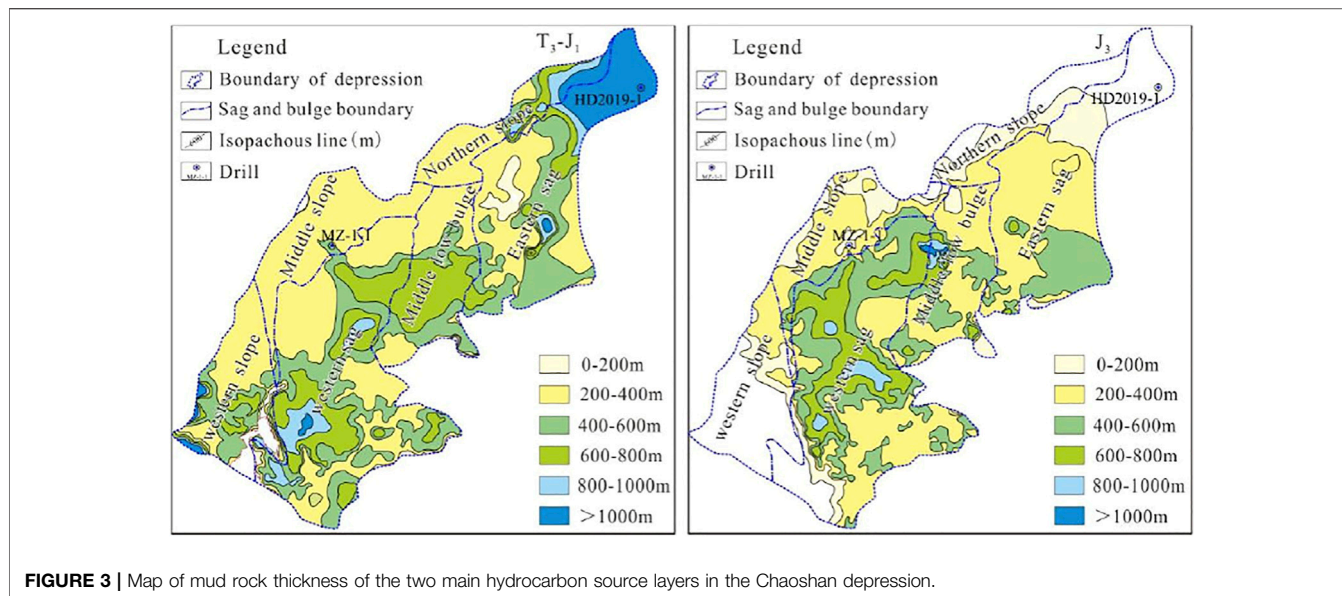


FIGURE 3 | Map of mud rock thickness of the two main hydrocarbon source layers in the Chaoshan depression.

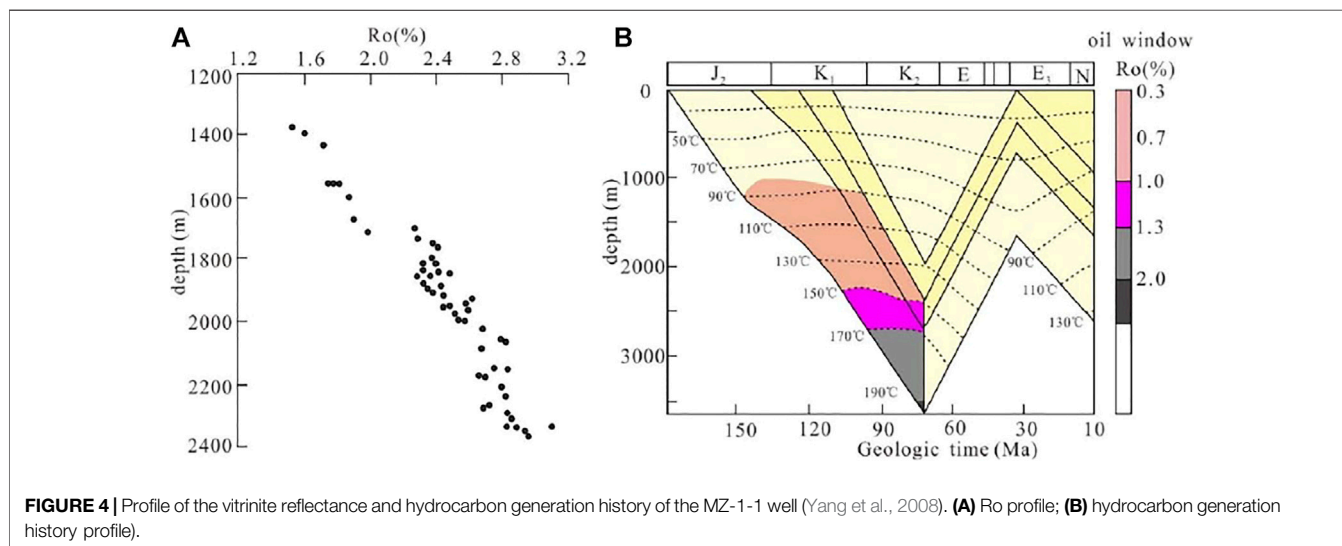


FIGURE 4 | Profile of the vitrinite reflectance and hydrocarbon generation history of the MZ-1-1 well (Yang et al., 2008). (A) Ro profile; (B) hydrocarbon generation history profile.

were of organic matter type II<sub>2</sub>-III (Yang et al., 2008; Hao et al., 2009).

In the seismic section next to the MZ-1-1 well (Figure 2), the muddy rock layer featured medium-weak amplitude, weak continuous, and low-frequency or blank reflections. From interpretation of the seismic grid, both sets of source rocks thickened outward in various directions from the drilled high Mesozoic (Figure 3). The T<sub>3</sub>-J<sub>1</sub> mudstone layer becomes much thick, larger than 1000 m to the northeast region of the eastern sag over where the HD2019-1 well was drilled. The J<sub>3</sub> mudstone layer also thickens, to generally 400–800 m, toward the middle low bulge and the western sag, prevailing in the NE-SW direction.

The mud hydrocarbon source rock of the J<sub>3</sub> mainly develops in the lower layer, its seismic facies characteristics are weak

amplitude, medium-high frequency, medium-weak continuous, locally blank reflection, or chaotic reflection configuration (Figure 2), belonging to the bathyal-neritic deposition. This set of mud rock is distributed in the western sag, the middle low bulge, and the southern part of eastern sag, elongating in the NE-SW direction with stable thickness at about 400–800 m (Figure 3).

### Maturity of Hydrocarbon Source Rock

Organic matter maturity is forwardly modeled based on seismic tying with the MZ-1-1 well where the hydrocarbon source rocks lie mostly below 1700 m. The maturity value, Ro, generally tends to increase sub-linearly with the formation depth from top to bottom (Figure 4), greater than 2.0% below 1700 m, and up to 3.0% at the bottom of the medium-upper

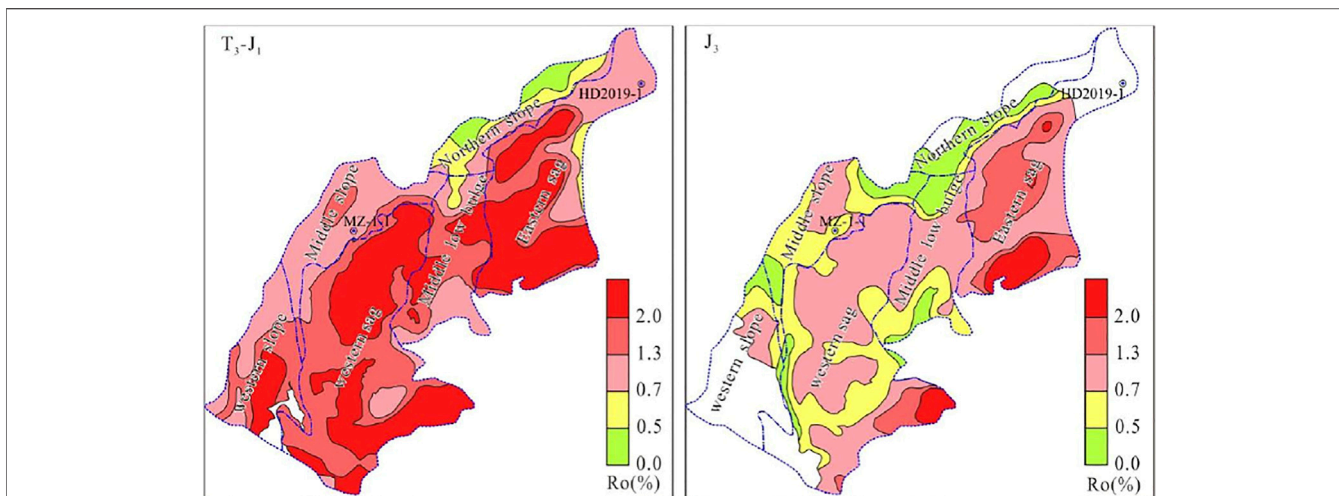


FIGURE 5 | Current Ro value distribution of the main hydrocarbon source rock of the Chaoshan depression.

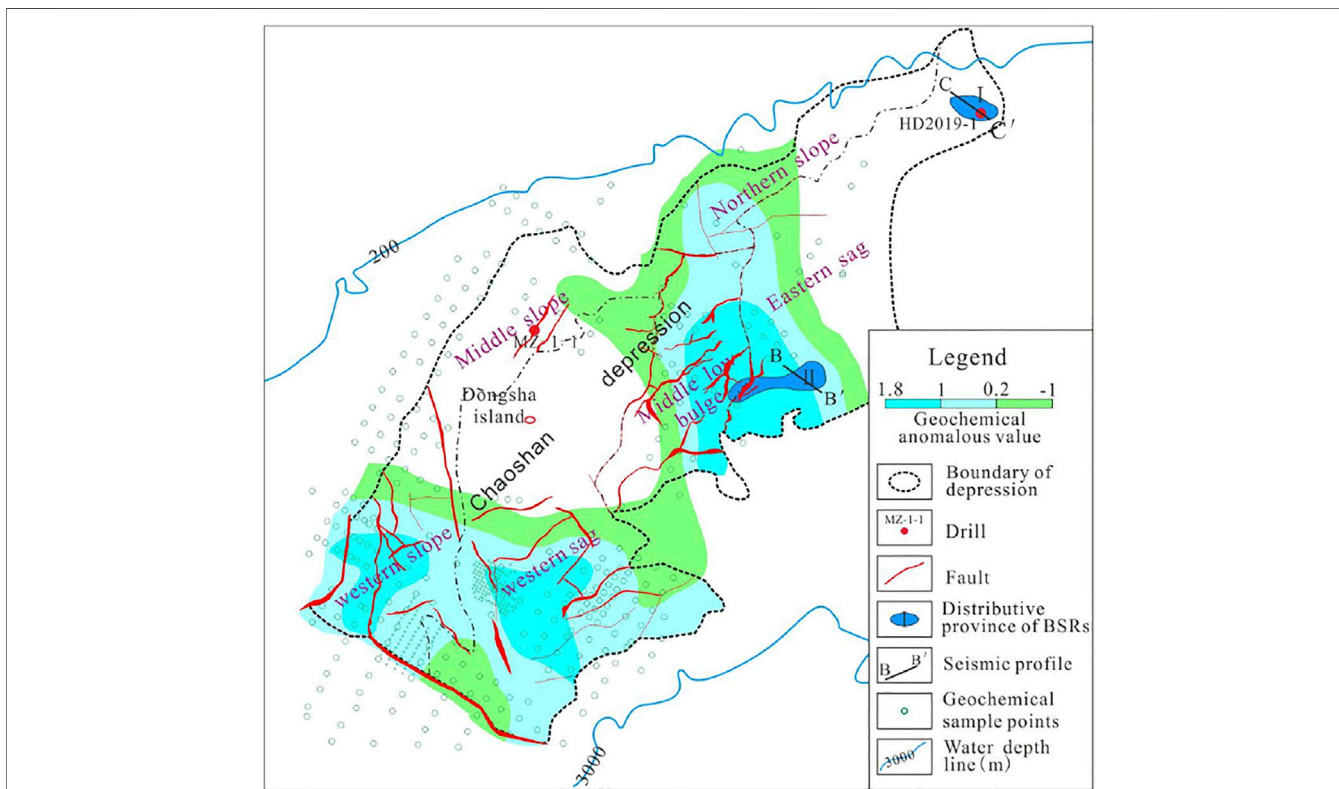
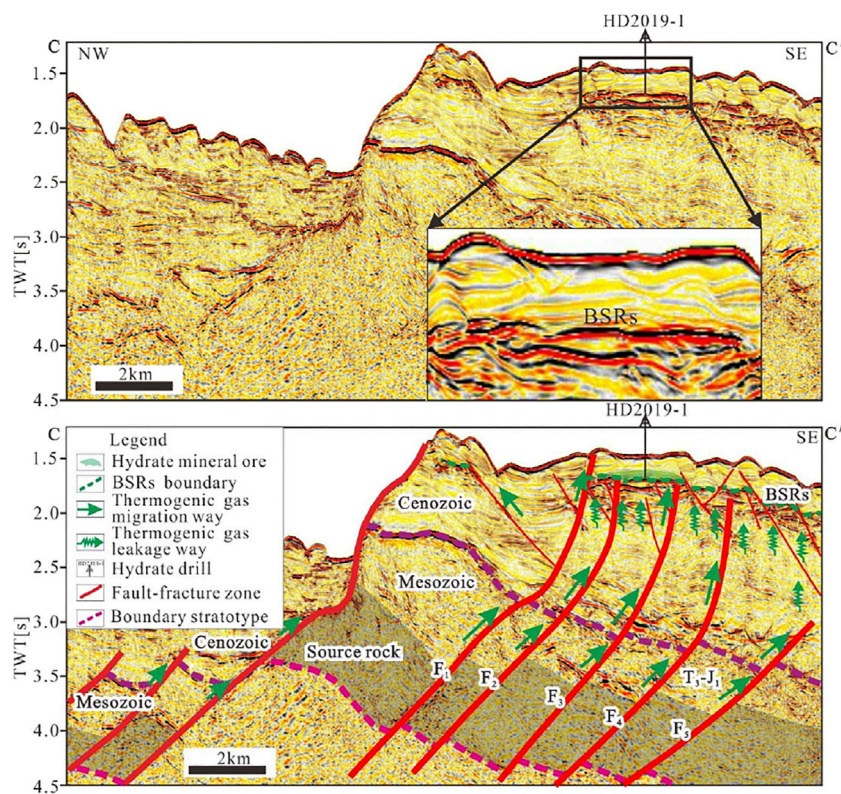


FIGURE 6 | Map of sample site and oil and gas geochemical anomalies, and Mesozoic faults in Chaoshan depression.

Jurassic (about 2400 m). The hydrocarbon source rock has entered the late phase of over mature (Yang et al., 2008). The middle-upper Jurassic source rock reached low maturity to the end of the late Jurassic period. The lower cretaceous reached the late hydrocarbon-generating stage in the middle of the late Cretaceous period (Figure 4).

On the plan view, the thickness of the T<sub>3</sub>-J<sub>1</sub> hydrocarbon source rock increased with the formation deposition. Nowadays, except for the northern part of the northern slope and the eastern part of the eastern sag which are still in the immature-low mature stage (Ro<0.7%), the rest of the regions have entered the mature hydrocarbon-generating stage. Most of the western sag, the



**FIGURE 7** | (C,C') profile hydrate accumulation pattern analysis graph (see line position in **Figure 1**).

southern part of the western slope, the southern-central part of the eastern sag, and the middle low bulge central regions are all entering the over mature stage ( $R_o > 2.0\%$ ) (**Figure 5**).

Except in the western slope,  $J_3$  hydrocarbon source rocks are in their immature stage in the middle slope, the northern slope, and the southern part of the middle low bulge; the low maturity-maturity stage is present in the other region. The central and southern part of the eastern sag and the southern part of the western sag enter into the gas generating stage ( $1.3\% < R_o \leq 2.0\%$ ), locally into the over mature stage (**Figure 5**). Therefore, the Chaoshan depression mainly developed two sets of hydrocarbon source rocks distributed in the NE-SW direction on the plane in  $T_3$ - $J_1$  and  $J_3$ . Most of the hydrocarbon source rocks are in their mature to over-mature stage nowadays. The potential for Mesozoic thermogenic gas generation is great.

### Fault-Fracture Passage

The Mesozoic in the Chaoshan depression faulted mainly in three strikes: NE, near SN, and near EW (**Figure 6**). The faults can be recognized as two generations, one during the Mesozoic and another during the Cenozoic Era (**Figure 7**). The earlier one has offset the Mesozoic sequences, generally with small throws, resulting in fragmented, weak, and chaotic reflections of the Mesozoic sequences. While the young one has more distributed fractures with lasting activity from the Pliocene to

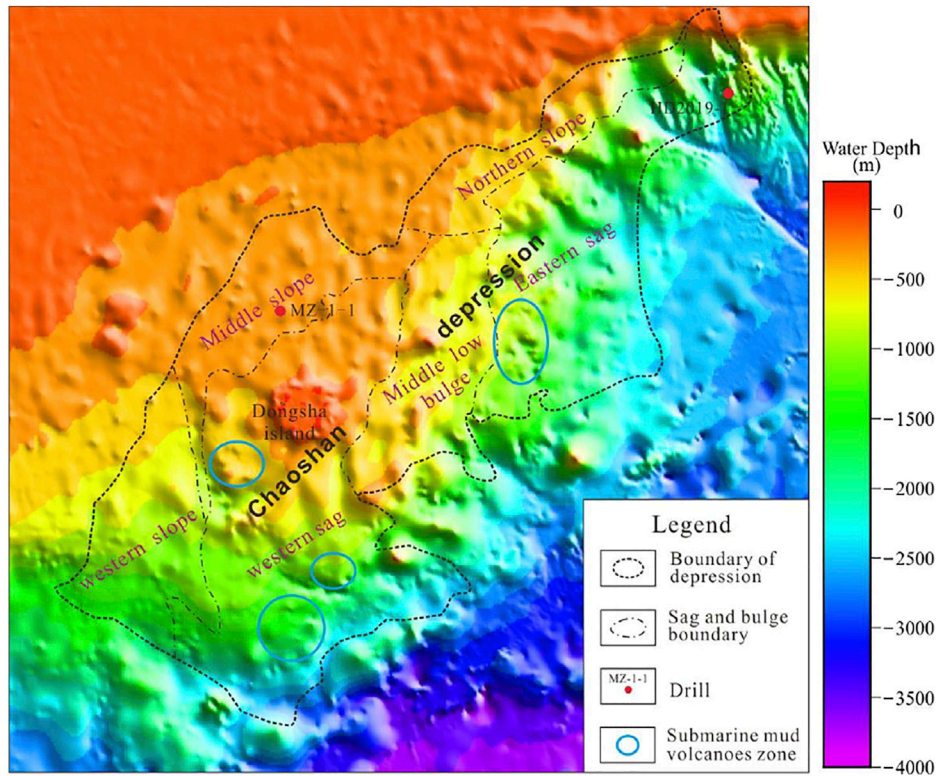
the Quaternary, which leads to instability and blank reflections of the young sediments.

Widespread bottom simulating reflectors (BSRs) present the seismic profiles over the northeastern most corner of the Chaoshan depression, named as the NO. I BSR anomaly area, where the 2013 and 2019 drilling surveys were conducted with discoveries of hydrates. As an example, seismic profile C-C' (**Figure 7**) reveals that BSRs coincidentally appeared above the fault-fracture zones, e.g.,  $F_1$ ,  $F_2$ ,  $F_3$ ,  $F_4$ ,  $F_5$ , and others. The association of the fault deep into the Mesozoic and fractures within the shallow covering sediments form good channels for the thermogenic gas to migrate vertically upward and diffuse as a hydrate ore body as an expression of the BSRs.

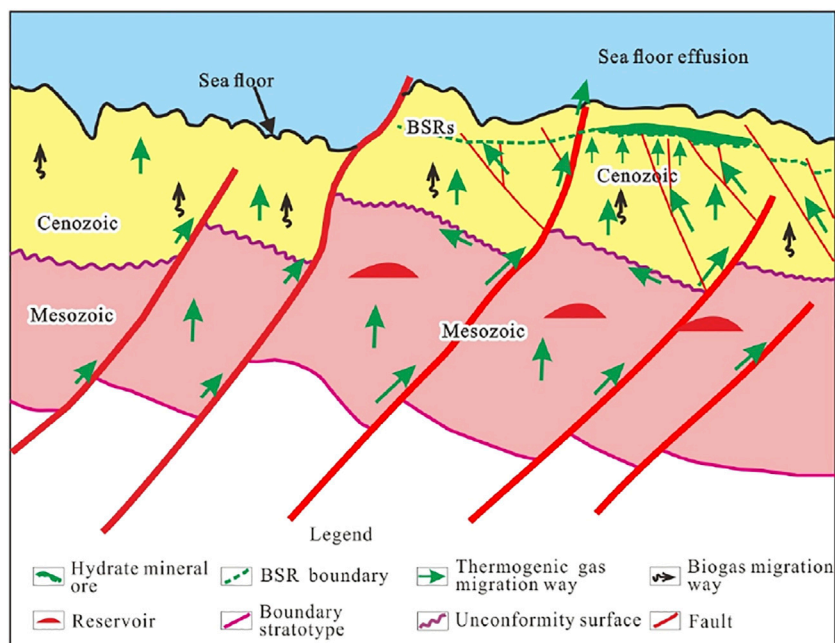
### Hydrocarbon Leakage

Submarine leakage of hydrocarbon leads to a geochemical anomaly on the seafloor. A quantified geochemical anomaly is calculated as described previously by normalization of five tested items over the sampled region. Its relative variation reflects the varying extent of hydrocarbon leakage.

**Figure 6** shows that there are three obvious geochemical anomaly areas in the Chaoshan depression, i.e., in the western slope, the southern part of the western sag, and the junction area of the middle low bulge and the southern part of the eastern sag. They are potential areas of hydrocarbon leakage. Coincidentally, these areas are distributed with numerous submarine mud



**FIGURE 8 |** Distribution map of the submarine mud volcanoes in the Dongsha Waters (mud volcanoes according to Yan et al., 2017; Yan et al., 2022).



**FIGURE 9 |** The schematic model for gas hydrate accumulation in the Chaoshan depression.

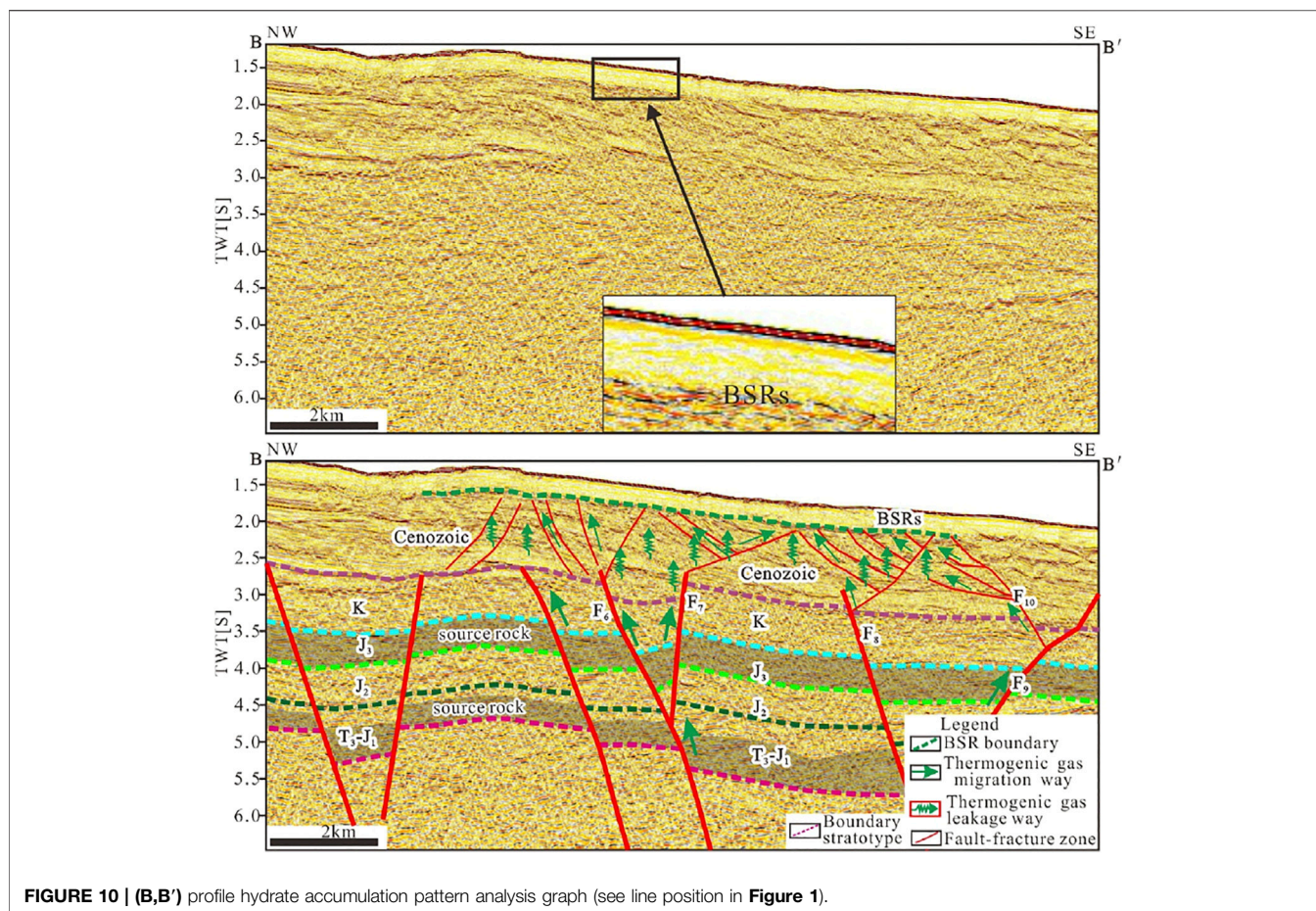


FIGURE 10 | (B,B') profile hydrate accumulation pattern analysis graph (see line position in Figure 1).

volcanoes (Figure 8) which also usually indicates extensive leakage of oil and gas (Yan et al., 2017).

## DISCUSSION

### Accumulation Model of Hydrates Over the Dongsha Waters

The overlap map of the geochemical anomalous area and the Mesozoic fault distribution shows a clear correlation between them (Figure 6). The geochemical anomaly is often high over the fault zones.

Most of the mapped faults cut through the two sets of source rocks in the Mesozoic, and break to the Cenozoic. The Cenozoic in this area is thin, generally, less than 1000 m, and does not have the gas source foundation for the formation of thermogenic gas. Therefore, it can be concluded that the hydrate thermogenic gas in this area mainly comes from the Mesozoic.

The thermogenic gas in the lower part of the Chaoshan depression hydrate ore body in Dongsha Waters comes from the Mesozoic (Figure 9). The deep region's fault-fractures communicate the temperature and pressure stability region of the hydrate and the Mesozoic hydrocarbon source rock, and the deep thermogenic gas is migrated along the transport system to the overlying formation and mixed with the microbial gas, eventually

forming hydrate. The fault plays a key role in the process of hydrate accumulation in the region. The Mesozoic fault development area is the main leakage area of thermogenic gas, and the gas source of thermogenic gas in this area is sufficient.

### Prediction of Hydrate Development Area in the Dongsha Waters

Apart from the northeastern most corner of the Chaoshan depression, the junction area of the middle low bulge and the southern most part of the eastern sag (Figure 6) is also found with a large span of clearly visible BSRs (Figure 10) over where high organic carbon is seen from results of the geochemical survey (Figure 6). Here the Mesozoic sequences develop more completely, with the  $T_3-J_1$ ,  $J_3$  hydrocarbon source rock entering into a mature-over mature period. Similar fault-fractures, such as  $F_6$ ,  $F_8$ , and  $F_9$ , cut deep to Mesozoic, and branch upward as  $F_7$ ,  $F_{10}$ , and more fractures (Figure 10) connecting with them, forming well passages for the thermogenic gas to migrate upward to the Cenozoic. Moreover, abundant authigenic carbonate nodules and deep-water fauna, e.g., shells, coral, and sponges, are found from dredged samples over some of the mud volcanoes by the area, which implies vigorous leakage of hydrocarbon (Zhong et al., 2020; Yan et al., 2021). Given the gas leakage condition and appearance of BSRs, the junction area of the middle low bulge



and the southern most part of the eastern sag can be utilized as a future drilling target.

## Implication of the Gas Source From Mesozoic

The oil and gas that leaked from the Mesozoic becomes the main source of thermogenic gas of the natural gas hydrate over the Dongsha Waters. The remaining hydrocarbon still can be traced through future exploration considering their wide distribution.

## CONCLUSION

- 1) By regional correlation with previous drilling results of MZ-1-1, the Mesozoic source rocks are widely distributed over the Dongsha Waters, including the northeastern corner of the Chaoshan depression where hydrates were drilled. They source rocks are well matured to produce sufficient thermogenic gas contributing to hydrates.
- 2) Geochemical anomalies hinting at the micro-leakage of oil and gas from the deep are well correlated with zones of the Mesozoic fault-fractures which act as good transport channels for the thermogenic gas to leak and diffuse.

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- 3) Enrichment of the Mesozoic thermogenic gas source in the gas hydrate is of great significance for hydrate and Mesozoic petroleum exploration.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

## AUTHOR CONTRIBUTIONS

The author CF and GZ completed the main body of the paper. MS calculated the thickness map. Others participated in the preparation of the map.

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