



# Thrust Faults Promoted Hydrocarbon Leakage at the Compressional Zone of Fine-Grained Mass-Transport Deposits

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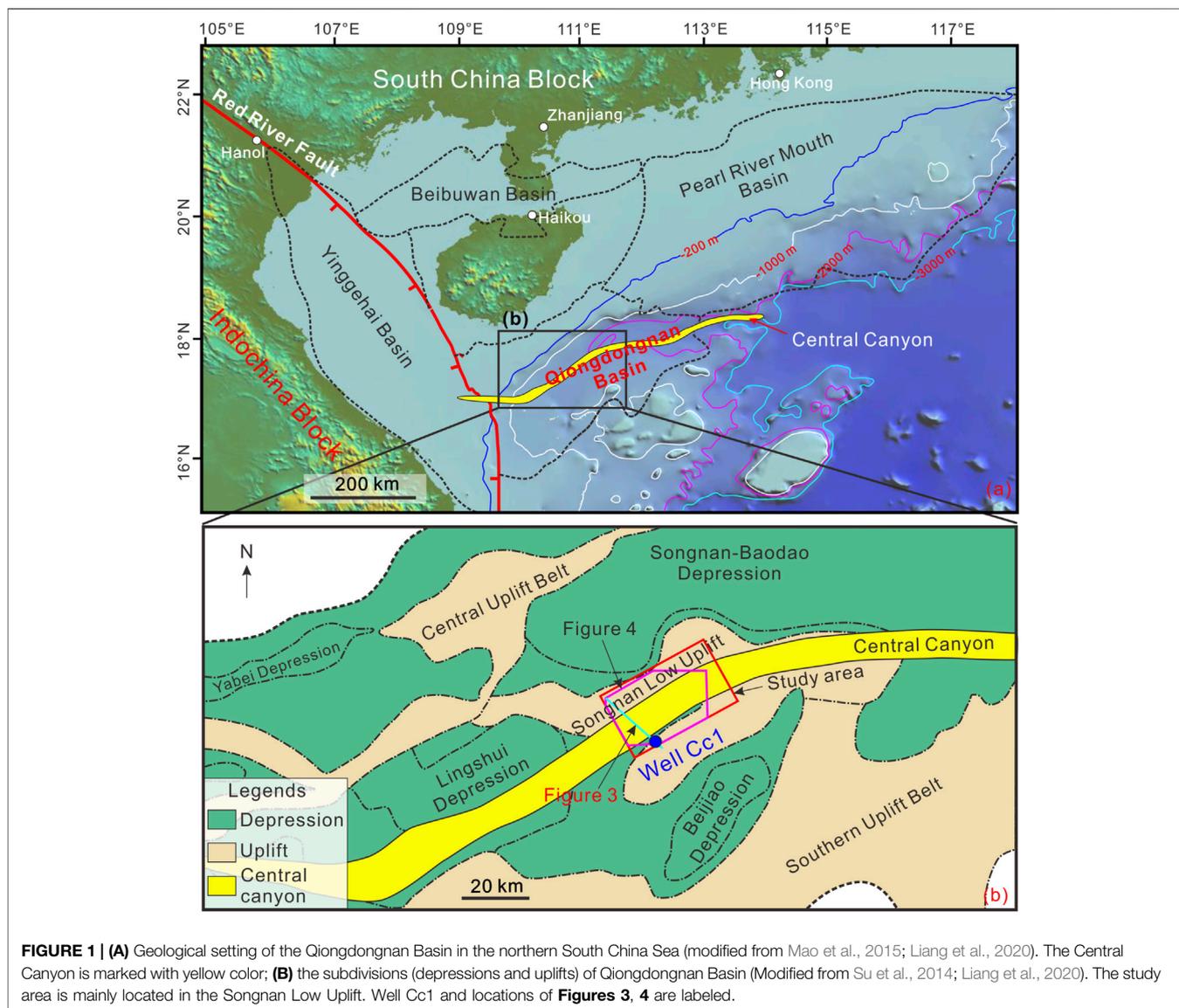
Fine-grained mass-transport deposits (MTDs), especially their compressional toe zones, are traditionally considered as effective seal in constraining the vertical fluid migration underneath. However, this study documents thrust faults at the compressional toe zone of fine-grained MTDs that could disaggregate the seal competence and promote vertical fluid flow. The investigated MTD referred to as MTD-a lies directly over a large hydrocarbon reservoir that is located within the Central Canyon of northern South China Sea, which is examined by using high-resolution 3D seismic and borehole data. Thrust faults and irregular blocks composed of coarse-grained sandstones are observed in the compressional zone of the MTD-a's toe. More importantly, seismic evidence (e.g., enhanced seismic reflections) suggests that a large amount of hydrocarbons from the underlying reservoir penetrated through the MTD-a along these thrust faults and charged into the coarse-grained sandstone blocks. This clear evidence of thrust faults compromising the MTD's seal effectiveness and thus facilitating the vertical fluid flow through the non-permeable strata demonstrate the importance of reassessing the seal capacity of MTD.

**Keywords:** mass-transport deposits, thrust fault, hydrocarbon leakage, block, South China Sea

## INTRODUCTION

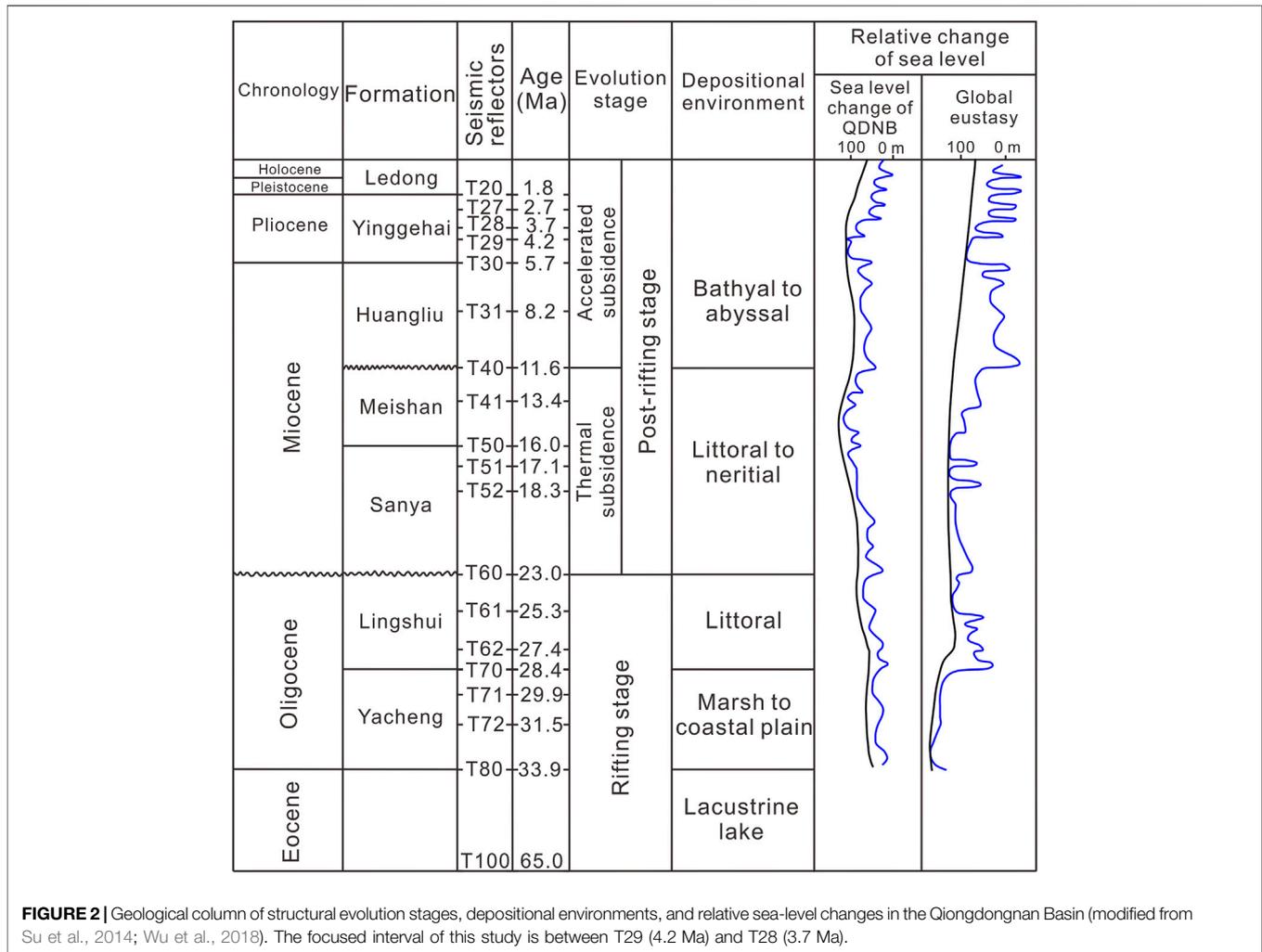
Mass-transport deposits (MTDs) widely occur at the continental margins and island flanks. They are usually composed of the headwall domain, translational domain, and toe domain (Martinsen, 1994; Lastras et al., 2002) and, accordingly, a systematic distribution of strain transferred from extensional structures in the headwall zone to compressional structures in the toe zone (Trincardi and Argnani, 1990; Canals et al., 2004; Frey Martinez et al., 2005). Thrust faults are an important component of MTDs at their compressional toe zones (Bull et al., 2009; Ogata et al., 2014; Alsop et al., 2017). They are usually caused by the translating material buttressing against a seabed obstacle (Lewis, 1971; Moscardelli et al., 2006) and typically affect the entire thickness of the MTD (Frey Martinez et al., 2005; Bull et al., 2009).

Thrust faults are mainly imaged by geophysical data (e.g., seismic reflection data) and shown as imbricated structures (Lamarche et al., 2008; Lackey et al., 2018). Because of the shear compaction and dewatering during the mass movement (e.g., decreases of porosities and permeability), MTDs,



especially those mainly composed of unlithified fine-grained sediments, are proposed as seal/barrier for the vertical fluid flow (Dugan, 2012; Alves et al., 2014; Sun and Alves, 2020). Furthermore, failed sediments are inclined to accumulate and thus thicken at the compressional toe zones (Moscardelli et al., 2006; Lamarche et al., 2008). Furthermore, the long-distance transportation of failed sediments at the toe zone is typically highly deformed and thus their fabrics are greatly damaged. These make the seal capacity of compressional toe zones of MTDs more effective. Although remnant blocks within MTDs are proposed to provide conduits for the vertical fluid flows (Alves et al., 2014; Gamba and Alves, 2015; Cox et al., 2020), no vertical flow pathways have been identified at the compressional toe zone until now.

In this study, the investigated MTD, here referred to as MTD-a, is immediately lying on a large hydrocarbon reservoir in the Qiongdongnan Basin (QDNB) of the northern South China Sea, based on high-resolution 3D seismic and borehole data. The aims of this study are 1) to characterize the MTD-a, including the internal structures, blocks, and free gas within the MTD-a; 2) to assess the seal completeness of the compressional zone of MTD-a; and 3) to explore the vertical fluid migration system in the study area. This study demonstrates that free gas has leaked from the underlying hydrocarbon reservoir and migrated into the blocks through thrust faults. Therefore, it provides clear evidence for the thrust faults at the compressional zone of MTDs serving as fluid pathways for the first time, which suggests that the seal completeness of MTDs should be reassessed where the thrust faults develop.



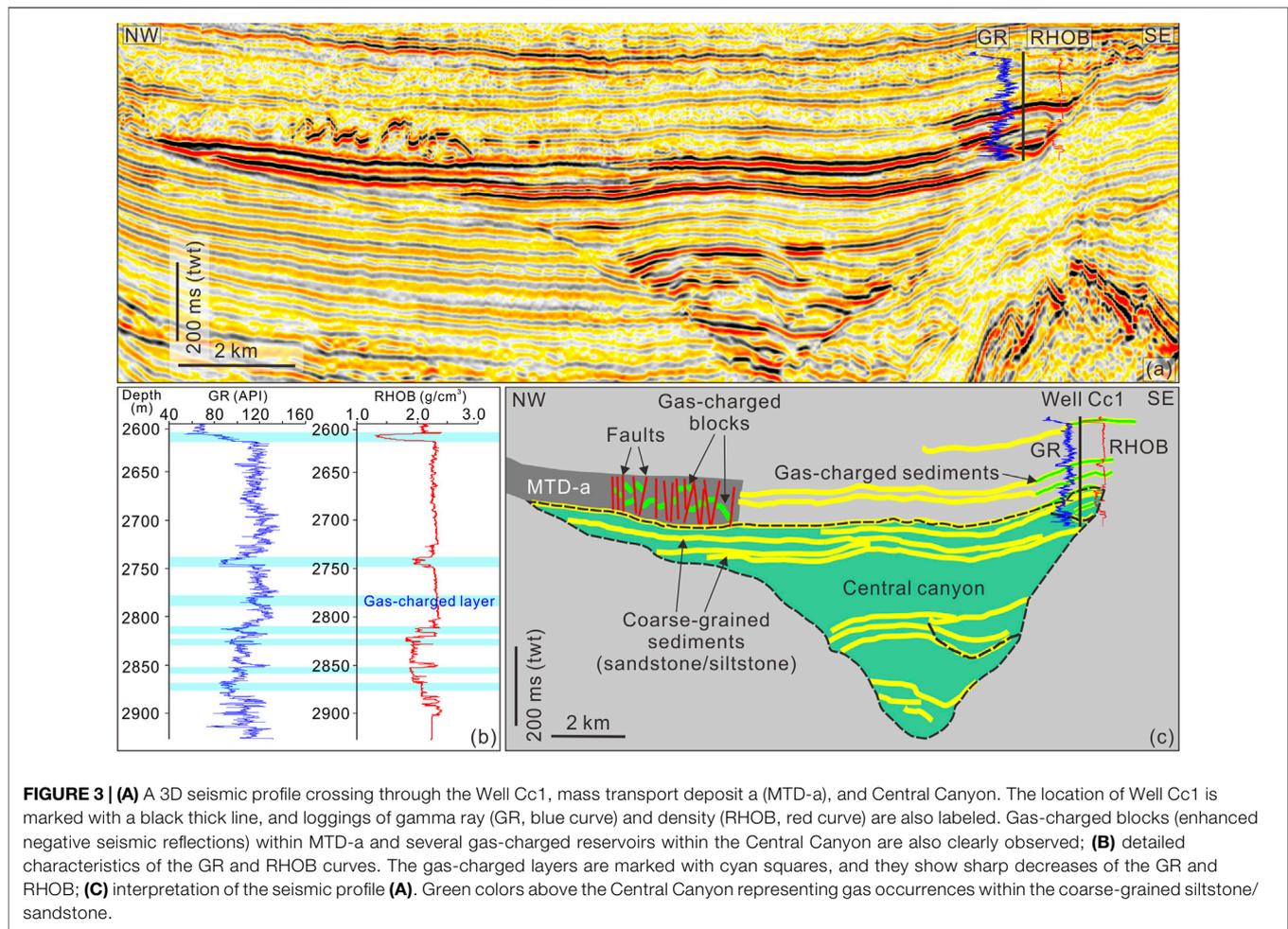
## GEOLOGICAL SETTING

The QDNB, one of the Cenozoic basins in the northern South China Sea located to the southeast of Hainan Island (**Figure 1**), covers an area of ~45,000 km<sup>2</sup> (Xie et al., 2008; Su et al., 2014). It comprises a few uplifts (massifs) and depressions (sags) (**Figure 1B**). The QDNB formed through two-stage tectonic evolutions, the Eocene-Oligocene rifting stage and the Miocene-to-Present post-rifting stage (**Figure 2**) (Gong and Li, 1997; Wu et al., 2008). During the rifting stage, deposits from the marsh-to-coastal plain Yacheng Formation and the littoral Lingshui Formation formed the main source rocks in the QDNB (Zhu et al., 2009). The post-rifting strata are composed of the littoral to neritic Sanya and Meishan formations, as well as the bathyal to abyssal Huangliu, Yinggehai, and Ledong formations (**Figure 2**) (Gong and Li, 1997; Zhu et al., 2009).

The QDNB is petroliferous, especially along the axis of the Central Canyon where numerous hydrocarbon fields have been found (Zhu et al., 2009; Wang Z. et al., 2015; Chen et al., 2015). The Central Canyon is > 425 km long and 3–16 km wide (Su

et al., 2014). Its deep incision into the strata as old as 8.2 Ma was fully filled at ~4.2 Ma (Liang et al., 2020). Moreover, the Central Canyon is mainly filled by the fine-grained mudstone and layered coarse-grained sandstone that acts as hydrocarbon reservoir (Wang Z. et al., 2015). After ~4.2 Ma, multiple MTDs are draped on the Central Canyon strata and formed the seal for the hydrocarbon reservoir (Liang et al., 2020).

MTDs widely developed in the QDNB and those in the southern QDNB (Huaguang Sag) are well studied (Sun et al., 2011; Wang et al., 2013; Wang D. et al., 2015). Those MTDs are cyclic with turbidities, such as triple packs of turbidities and MTDs, which are probably related to the sea-level changes (Sun et al., 2011). Moreover, the reactivation of major faults and associated volcanism in the late Miocene were proposed as the dominant trigger mechanisms for those MTDs (Wang et al., 2013). MTDs also frequently occurred in the central QDNB, as mentioned above (Liang et al., 2020). They may source from the northern slope area, western slope area, or Guangle Massif (Cheng et al., 2021) and mainly formed after ~4.2 Ma (Liang et al., 2020). Moreover, the slope overstepping



resulting from high sediment supply likely triggered the slope instability (Qin et al., 2015; Liang et al., 2020). The occurrence of MTDs greatly changed the sediment dispersal pattern in the Central Canyon and thus influenced the hydrocarbon systems (reservoirs and seals) in the study area (Li et al., 2015; Liang et al., 2020).

## DATA AND METHODS

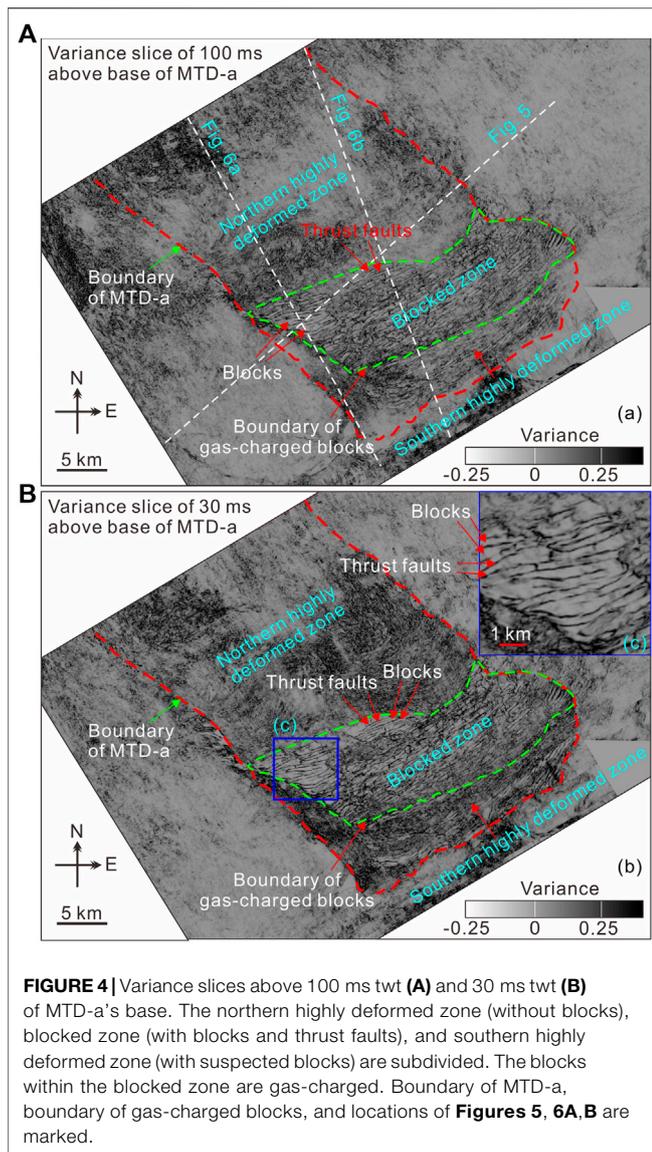
The time-migrated 3D seismic reflection data used in this study cover an area of  $\sim 1,050 \text{ km}^2$  and were provided by the China National Offshore Oil Corporation (CNOOC). It was acquired in 2010 with 3,000-m-long streamers consisting of 240 channels at a spacing of 12.5 m and a sample rate of 4 ms. The bin spacing of the 3D seismic data is 25 m in the crossline and 12.5 m in the inline. The dominant frequency of the focused strata is  $\sim 35 \text{ Hz}$ , and thus, a vertical resolution of  $\sim 20 \text{ m}$  is calculated, based on the strata velocity of 2,800 m/s from the Well Cc1 (Figure 1B). The 3D seismic reflection data are zero-phase processed and displayed with the Society of Exploration Geophysicists (SEG) normal polarity, whereby a downward increase in acoustic

impedance corresponds to a positive reflection event (red on seismic profiles) (Brown, 2004). Exploration well Cc1 is used for the lithology and strata velocity correlation. This well was located at the flank of the Central Canyon and drilled through several gas-charged sandstone layers (Figure 3). To better image the blocks, a variance attribute is used in this study (Figure 4). The variance attribute measures the variability in shape between seismic traces (Brown, 2004). It is directly derived from the processed data and thus is free of interpreter bias. The variance attribute is typically used to map structural and stratigraphic discontinuities (e.g., blocks, faults, and channels).

## RESULTS

### General Characteristics

The most prominent structure in the study area is the “V”-shaped Central Canyon. It quickly widens upward, and the fill sediments onlap onto its walls (Figures 3A,C, 6). The strata are mainly parallel/subparallel along the axis of the Central Canyon (Figure 5), and tapering/onlapping seismic



reflections are only occasionally observed along the axis (**Figure 5**). Many boreholes have targeted the hydrocarbon-rich Central Canyon and show that the strata mainly comprise fine-grained mudstone (Su et al., 2014; Liang et al., 2020). Coarse-grained siltstone and sandstone are also observed within the Central Canyon (**Figure 3C**), which is the main hydrocarbon reservoir (Wang Z. et al., 2015).

Multiple MTDs characterized by chaotic/blanking seismic reflections are observed above the Central Canyon, separated by continuous seismic surfaces (**Figures 3A, 5, 6**). This study is focused on the lowermost MTD, here named as MTD-a, which is directly draped on the Central Canyon (**Figure 3A**).

Many irregular blocks, characterized by short enhanced-amplitude, negative-polarity seismic reflections are identified inside the MTD-a (**Figures 3A, 5–7**). Although there is no well directly through these blocks, referencing the Well Cc1's layered

structure leads to a reasonable assumption that the blocks are mainly composed of sandstones (**Figure 3**). The blocks are surrounded by fine-grained mudstone (chaotic seismic reflections). The head zone of MTD-a has not been imaged, because of the limitation of 3D seismic coverage (**Figure 4**). It may have originated from the slope of QDNB to the north (**Figure 1**) and flowed toward the southeast part, judging from the extension of MTD-a (e.g., the direction of the lateral margins) (**Figure 4**). In the 3D seismic coverage, MTD-a could be divided into three subzones, such as a northern highly deformed zone, a blocked zone, and a southern highly deformed zone (**Figure 4**). No macroscopic blocks could be observed within the northern highly deformed zone, and it is mainly composed of chaotic seismic reflections (**Figure 6**). In the blocked zone, blocks float within the fine-grained strata (mudstone) and they are separated by high-angle thrust faults (**Figure 5**). There are suspected blocks observed on the variance slices in the highly deformed zone to the south (**Figure 4**). However, the seismic identification of these structures is not definitive (**Figures 3A, 6**).

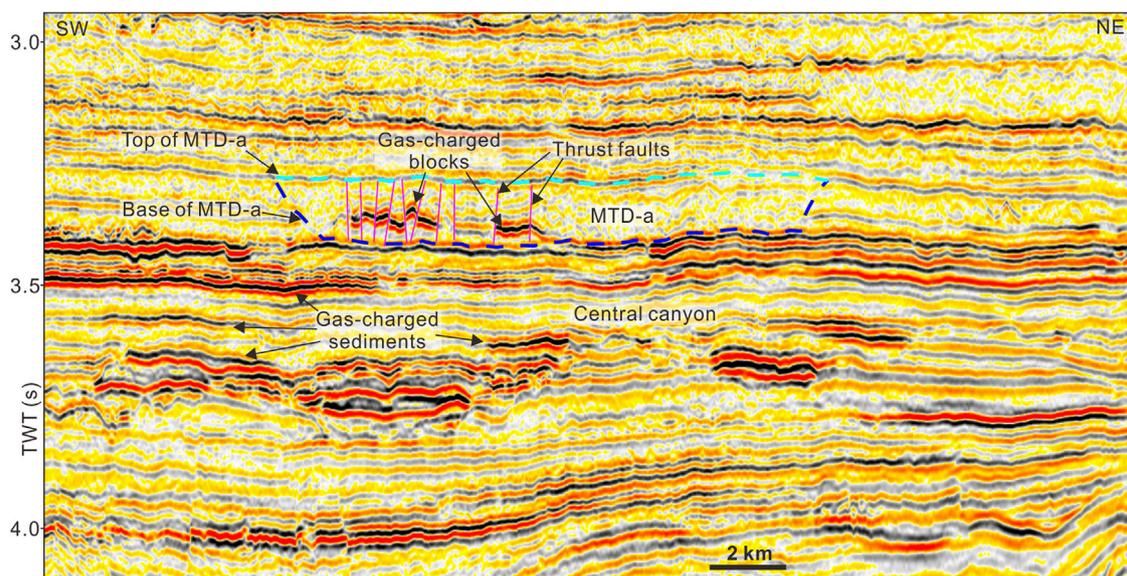
## Blocks

A total of 306 seismic-scale irregular blocks were recorded in the study area, characterized by enhanced seismic reflections as mentioned above, and are observed in the toe zone of MTD-a, especially those close to the southeastern boundary (blocked zone; green dashed zones in **Figure 4A**). However, the blocks are rarely observed at the distal termination part of MTD-a (southern highly deformed zone; **Figure 4A**). They are mainly bounded by thrust faults to their northwestern and southeastern sides and surrounded by chaotic seismic reflections (**Figures 6, 7**). In other words, they “float” within the chaotic seismic reflections. Although they are bounded by the thrust faults, the blocks are close to each other and some of them are even directly connected (**Figure 7**).

The irregular blocks are distributed in a linear fashion in plain view with orientations of E–W at the northwestern corner of the blocked zone and NE–SW at the left blocked zone (**Figure 4**). The dips of blocks are perpendicular to their strike extensions, and a few blocks are nearly horizontal elongation without any dips (**Figure 5**). The lengths of blocks range from ~0.20 to ~6.34 km with an average of ~1.48 km, while the blocks' widths are between ~0.10 and ~2.05 km, with an average of ~0.27 km. There is no apparent relationship between the lengths and widths of blocks ( $R^2 = 0.03$ ; **Figure 8A**). The blocks cover an average area of ~0.44 km<sup>2</sup> ranging from ~0.02 to ~4.24 km<sup>2</sup>. The areas of blocks are moderately related to their lengths ( $R^2 = 0.54$ ; **Figure 8B**) and widths ( $R^2 = 0.50$ ; **Figure 8C**). The average height of blocks is ~42.4 m (~30.3 ms twt), and thus the total volume of blocks (total area × average height) is ~5.68 km<sup>3</sup>.

## Thrust Faults

A total of 350 seismic-scale thrust faults are identified in the blocked zone, which separate the blocks apart (**Figures 5, 7**).



**FIGURE 5** | A 3D seismic profile perpendicular to the extension of MTD-a shows its lateral boundaries. Gas-charged blocks are clearly observed within MTD-a. Central Canyon is mainly unfilled by layered sediments. Top and base of MTD-a are marked with cyan and blue dashed lines. See location in **Figure 4**.

Most of the thrust faults penetrate the whole MTD-a and terminate at the upper surface of the underlying Central Canyon strata (**Figure 6**). However, some small-scale thrust faults are mainly located in the upper part (above the blocks) of MTD-a (**Figure 7B**). The lengths of thrust faults range between ~0.27 and ~4.92 km with an average of ~1.4 km (**Figure 8D**). The strikes of thrust faults mainly extend between 40° and 70° (~84% of the total thrust faults) (**Figure 8D**). Less thrust faults strike 90°–147°, and they usually have short vertical extensions (<1.0 km; **Figure 8D**). Accordingly, the thrust faults mainly incline 130°–160° (37% of the total thrust faults) and 320°–340° (45% of the total thrust faults; **Figure 8E**). The dips of thrust faults range from ~25° to ~87°, and most of them (90%) are between ~30° and ~70° (**Figure 8F**).

## Free Gas

Enhanced seismic anomalies characterized by negative reflections are observed in the Central Canyon and MTD-a's blocks (**Figures 3A, 5–7**), which is similar to the typical seismic characteristics of free gas (e.g., Judd and Hovland, 2007; Løseth et al., 2009; Sun et al., 2017). In fact, the exploration well Cc1 drilled through these enhanced seismic anomalies and confirmed that they are gas-charged sandstones (**Figures 3A,C**). Furthermore, these gas-charged sandstones characterized by sharp decreases of gamma ray (GR) and density (RHOB) are surrounded by fine-grained mudstones (**Figure 3B**). Accordingly, the irregular blocks within MTD-a could be interpreted as the counterparts of sandstones (**Figure 3C**). Moreover, the enhanced negative seismic reflections of blocks (**Figures 3A, 5–7**) indicate that free gas also charged into them. The average porosity of sandstone from well Cc1 is ~29.6%, and that of gas saturation

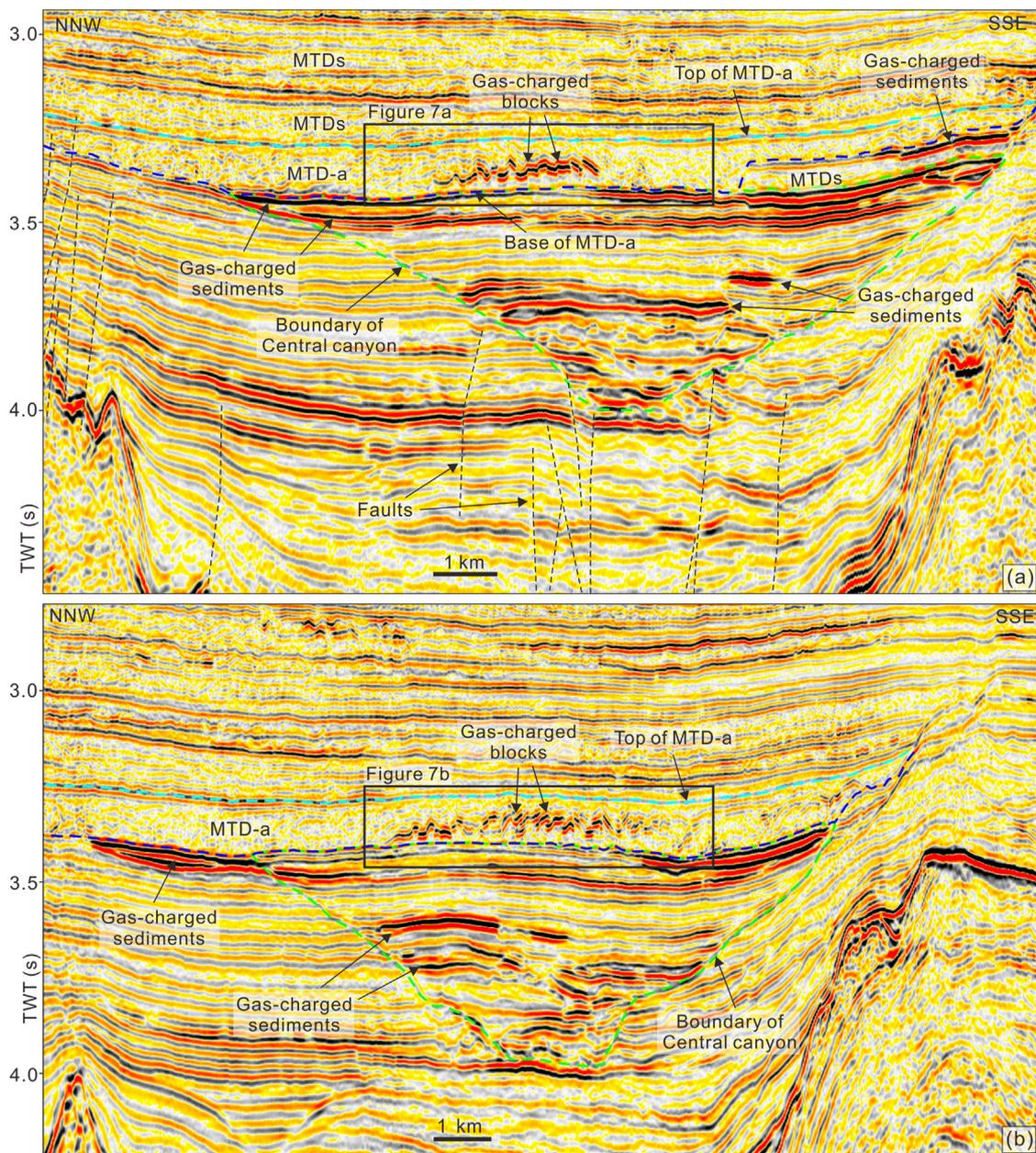
is ~71.2%; hence, the volume of free gas stored within the MTD-a' blocks can be as high as  $\sim 1.2 \times 10^9 \text{ m}^3$ .

## DISCUSSION

### Seal Disintegration and Vertical Hydrocarbon Migration

Fine-grained MTDs usually have decreased porosities and permeability, because of shear compaction and dewatering during their emplacement (Piper et al., 1997; Shipp et al., 2004; Sawyer et al., 2007; Dugan, 2012; Sun and Alves, 2020). Therefore, they usually act as effective seal to hinder the vertical migration of fluids (Alves et al., 2014; Sun and Alves, 2020). Remnant blocks that break through the MTDs could occasionally support the vertical fluid migration (Gamboa and Alves, 2015; Cox et al., 2020). However, there are no reports about vertical fluid flow in the compressional toe zone of MTDs as yet, where the compressional stress in the toe zone is proposed to strengthen the seal capacity of sediments.

Gas-charged blocks within MTD-a indicate that significant amounts of hydrocarbon have leaked from the gas field underlying the MTD-a (**Figures 5–7**). Because the blocks are surrounded by fine-grained sediments and are not directly connected with the underlying gas reservoir, the thrust faults are believed to act as the primary pathways for vertical fluid migration. Normally, the thrust faults in the compressional environment would be tight/closed to barrier fluids (Elmore et al., 2003; Micklethwaite, 2008). However, the thrust faults, likely with fractured medias, are mechanically weak zones (e.g., Lacroix et al., 2014; Cook et al., 2020), and they would likely reactivate under overpressure due to the underlying



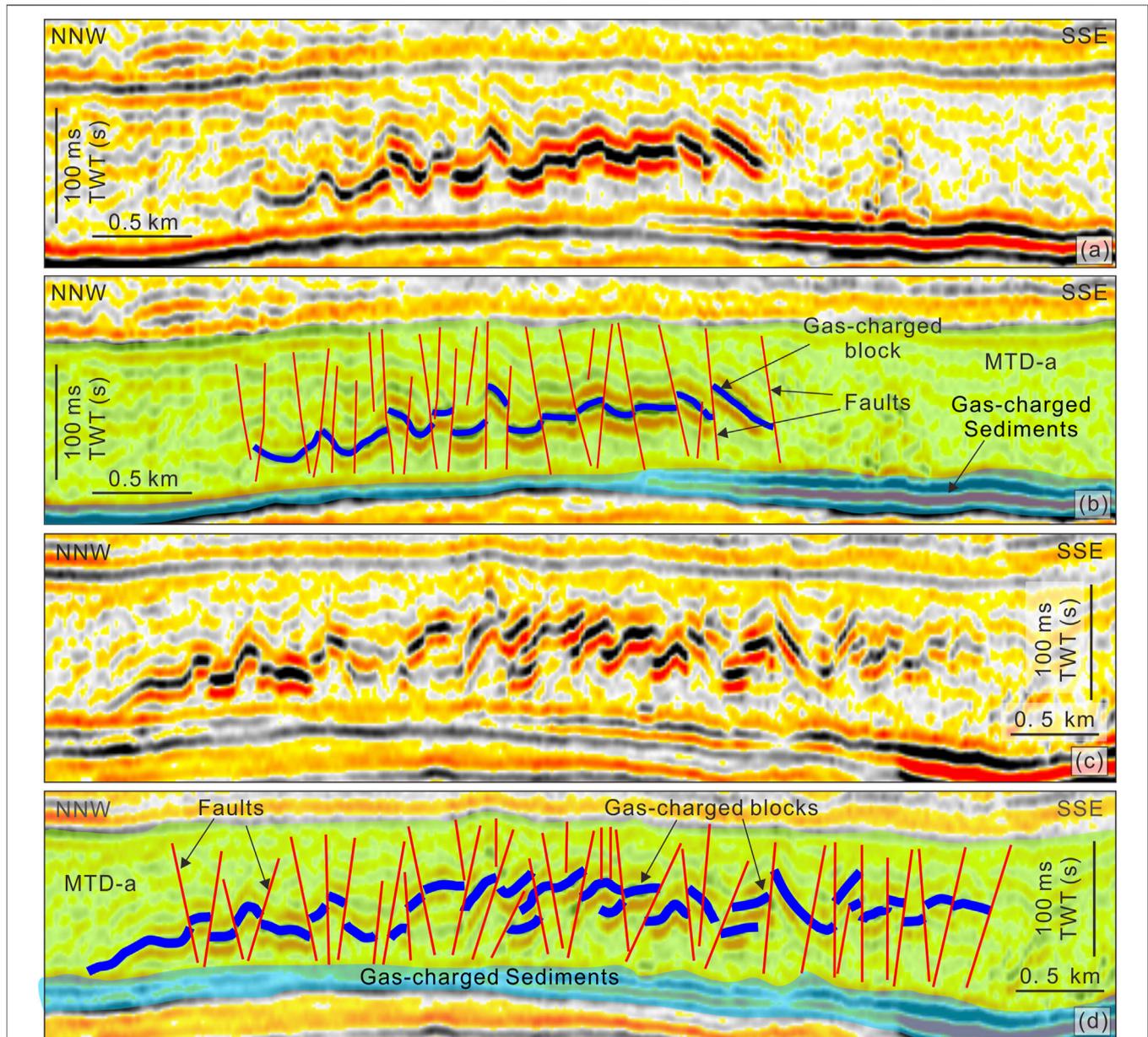
**FIGURE 6** | 3D seismic profiles nearly parallel to the extension of MTD-a. MTD-a directly overlies the Central Canyon. Several gas-charged layers (enhanced negative seismic reflections), especially the uppermost layers, occurred within the Central Canyon. Gas-charged blocks within the MTD-a are surrounded by chaotic seismic reflections, interpreted as mudstone. Normal faults developed below the Central Canyon, and they provide the main pathways for the deep-seated hydrocarbon migration. Locations of **Figures 7A,B** are marked with black squares.

accumulation of hydrocarbons. Moreover, the blocked zone has weaker deformation compared to the northern and southern highly deformed zones where the failed sediments are probably fully mixed (**Figure 4**). The less mixture of sediments in the blocked zone would partly keep the fabrics of the strata, which is also in favor of reactivation of the thrust faults. This study documents the thrust faults at the compressional zone of MTDs to serve as fluid pathways for the first time. It also indicates that the fabric heterogeneity plays an important role

on the seal completeness, and certain factors (e.g., overpressure) may trigger the disintegration of seal, even for the fine-grained sediment-dominated compressional zones of MTDs.

## Hydrocarbon Migration and Accumulation System

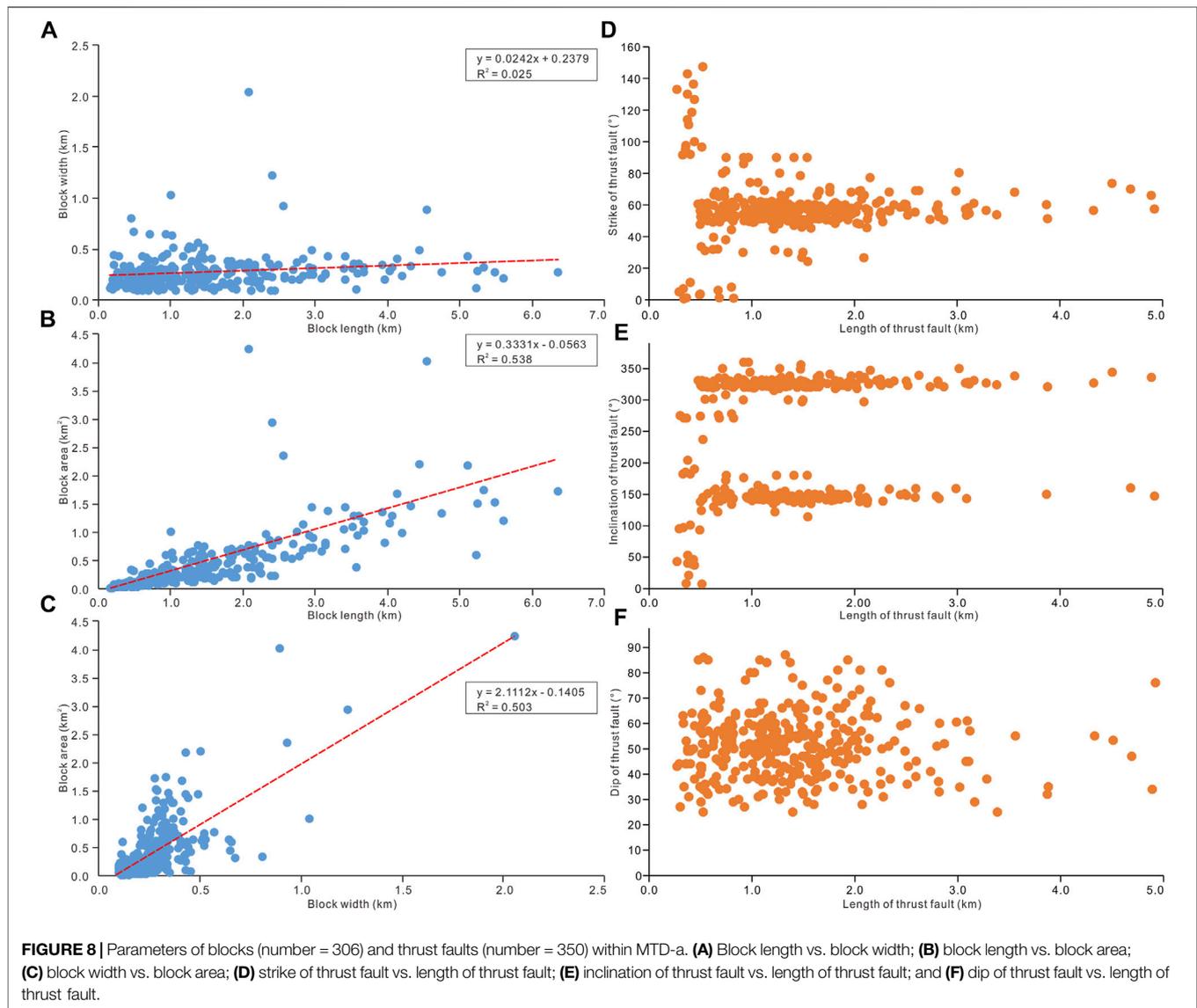
The hydrocarbon migration and accumulation system in the study area can be updated through this study together with



**FIGURE 7 |** Enlargements of seismic profiles **(A,C)** and their interpretation **(B,D)** showing the details of blocks and thrust faults within MTD-a. MTD-a directly lies on the hydrocarbon reservoir. Thrust faults link the underlying hydrocarbon reservoir and MTD-a' blocks and provide pathways for the gas leaking upward.

previous studies (Zhu et al., 2009; Li et al., 2017). The deeply buried coal-bearing strata of the lower Oligocene Yacheng Formation serve as the main source rock in the QDNB (Huang et al., 2003). The source rock entered the peak gas-generation window during the late Miocene and Pliocene (Zhu et al., 2009). Hydrocarbon (gas) from the source rock migrated upward mainly along tectonic faults (Figure 6A) and charged into the reservoir of the Central Canyon from the Pliocene to the present (Wang et al., 2014). Within the Central Canyon, the interconnected coarse-grained siltstone/sandstones provided

the lateral and vertical hydrocarbon migration pathways (Figure 9). Finally, the hydrocarbon accumulated at the topmost part of the Central Canyon where the reservoir is directly capped by the compressional zone of the fine-grained MTD-a (Figures 6, 9). The compressional zone of MTD-a is composed of a series of thrust faults and coarse-grained blocks, as mentioned above (Figure 3). Accompanying the gradual accumulation of hydrocarbon, overpressure would increase and finally exceed the yield strength of thrust faults. Therefore, the thrust faults would reactivate and allow



hydrocarbons would migrate upward along these faults and charge the blocks, as observed in this study (Figures 7, 9). This study indicates that a large amount of hydrocarbons ( $\sim 1.2 \times 10^9 \text{ m}^3$ ) has probably leaked from the main reservoir of the gas field. Furthermore, the hydrocarbon system including the hydrocarbon migration, accumulation, and leakage in the study area is probably still dynamic, and special attention should be paid to the seal completeness where thrust faults occur within the MTDs.

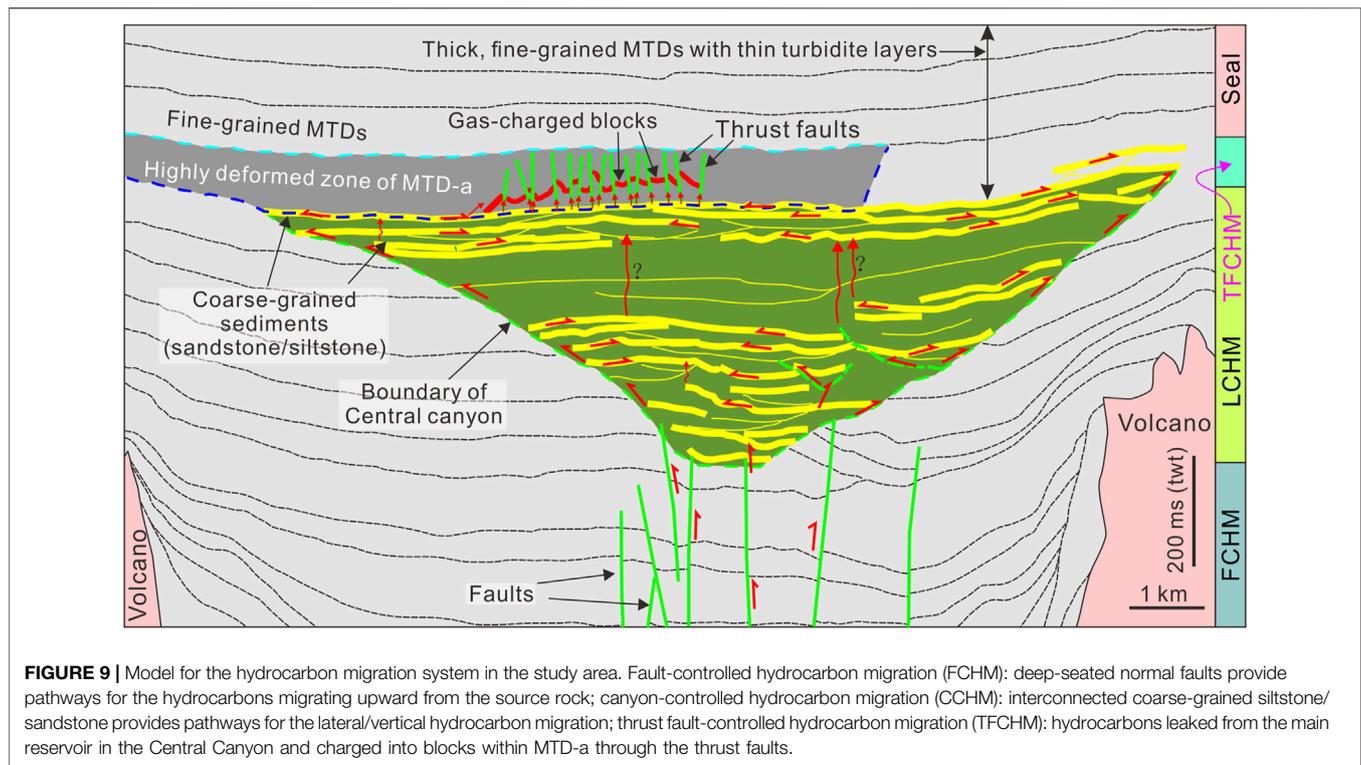
## CONCLUSION

This paper is focused on an MTD-a that is directly overlying a large gas field in the Central Canyon of the Qiongdongnan Basin (South China Sea), using high-resolution 3D seismic

data and borehole data. The main conclusions are drawn as follows:

- 1) Well-developed seismic-scale blocks and thrust faults are widespread in the compressional zone of MTD-a.
- 2) Thrust faults helped to penetrate MTD-a's seal and provided pathways for vertical fluid migration. This is the primary mechanism for as much as  $1.2 \times 10^9 \text{ m}^3$  of hydrocarbon to escape from the reservoir, migrate upward, and eventually accumulate in the sandstone blocks.

This study provided clear evidence for the thrust faults promoting fluid flow at the compressional zone of MTDs for the first time, which has important implication on the assessment of MTDs' seal competence and underlying reservoir completeness. Moreover, reevaluation of other fine-grained



MTDs assumed as seals is advised to reduce uncertainty in the sealing capacity of MTDs, particularly those displaying blocky and faulted textures.

## 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 author.

## AUTHOR CONTRIBUTIONS

QS is the principal author and primary seismic interpreter, and also writes and edits the paper. XX and SW contribute on the interpreting the seismic data, and writing/editing the paper. GY contributes on preparing the figures and writing the paper.

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**Conflict of Interest:** GY was employed by the company PetroChina Changqing Oil Field Company.

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