Research Article

Geological Characteristics of Mud Volcanoes and Diapirs in the Northern Continental Margin of the South China Sea: Implications for the Mechanisms Controlling the Genesis of Fluid Leakage Structures

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Mud volcanoes and diapirs are geological structures formed due to arch piercing or diapiric intrusion of ductile sedimentary materials into the overlying strata along high permeability channels. A detailed study on the processes controlling the formation of mud volcanoes and diapirs in the northern continental margin of the South China Sea is of vital importance to the exploration of economically viable oil and gas reservoirs and can be helpful to the exploration of natural gas hydrate in a sedimentary basin. The fluid seepage structures that occur in the Mesozoic and Cenozoic sedimentary basins of the northern South China Sea show significant differences in their morphological and tectono-structural characteristics. We used high-resolution seismic profiles and instantaneous frequency profiles to understand the mechanisms that are critical with respect to the differential development of the investigated piercement structures. Differences in stress field do not directly lead to the difference in the scale of mud volcanoes or diapirs. Fractures may play an important role in the formation of mud volcanoes and diapirs. The thickness of the sediment was found to have a strong impact on the formation of fluid leakage structures that thicker sediments are more conducive to the development of mud diapirs and the thinner one is more likely to form mud volcanoes.

1. Introduction and Rationale of the Study

Mud volcanoes and diapirs are piercement structures formed due to subterranean high pressure (P) imposed on ductile material in deep basins hosting relatively thick sedimentary sequences. These structures are produced by arching or diapiric intrusion into the overlying strata along high-permeability channels, such as zones of mechanical weakness (e.g., fractures and faults [1–4]). Mud volcanoes are formed when a mud slurry exudate is forced upwards, piercing the surface or the seafloor. Conversely, when the oozing, high-

plasticity material cannot pierce to the surface or the seafloor, mud diapirs are formed [2].

Piercement structures are widely distributed all over the world. Mud volcanoes have been reported from more than 40 continental regions and 20 seas around the world [1, 2, 5–9]. Among them, the Mediterranean Ridge, the Niger Delta, Azerbaijan, and the northern continental margin of the South China Sea host a huge number of mud volcanoes or mud diapirs [10–13]. Mud volcanoes and diapirs commonly occur in accretionary wedge regions subjected to compressive stress such as the Mediterranean Ridge [14–16] and

the Island of Barbados [17]. Less frequently, they appear in extensional provinces such as the Black Sea [18, 19] and the Southeastern Tyrrhenian Sea [20]. Furthermore, some mud volcanoes and diapirs are both associated with stretching and extrusion environments such as the Western Alboran Sea [21, 22].

Mud volcanoes and diapirs are structures of great geological significance. They are closely linked to the tectono-sedimentary evolution of basins and may play an important role in hydrocarbon migration and accumulation [1, 23–25]. Submarine mud volcanoes and diapirs can be important markers of deep-water petroleum and shallow gas hydrate deposits [26–30]. In addition, mud volcanic activity can be used as an important indicator of early oil and gas evaluation in sedimentary basins [31–33]. The large amount of methane (CH_4) emitted from mud volcanoes accelerates the greenhouse effect, contributing to climate changes on a global scale [1, 34, 35]. Lastly, diapiric and volcanic activities underneath geological basins are prominent indicators of neotectonic movements and may lead to fatal geological disasters [36, 37].

Previous studies on mud volcanoes and diapirs focused on various aspects, including their geological structure [2, 5, 8, 38, 39] and geochemical [8, 34, 40, 41] and geophysical [4, 36, 42, 43] signatures. Some of these researches tried to discuss the formation mechanism of mud volcanoes or diapirs (e.g., [9, 13]) and the relationships between the evolution of such piercement structures and hydrocarbon or gas hydrate accumulation [2, 44].

Investigating the genetic mechanisms of mud volcanoes and diapirs in the northern part of the South China Sea is of great significance for understanding the migration and accumulation processes of petroleum and gas. According to the analysis of geology, geophysics, geochemistry, biology, and thermodynamics of the South China Sea (e.g., [12, 43, 45–48]), hundreds of mud volcanoes and diapirs have been reported in the northern continental marginal basins of the South China Sea (Figure 1), i.e., the Yinggehai, Qiongdongnan, Pearl River Mouth, and Southwest Taiwan Basins. Previous studies mainly describe the types, morphology, development characteristics, and distribution of fluid leakage structures in one of these basins or inferred the source of fluid by combining seismic profile and geochemical analysis (e.g., [49]). These cannot sufficiently explain the differences in the formation processes of the mud volcanoes and diapirs developing in the northern South China Sea. At present, the mechanisms that control the formation of mud volcanoes and diapirs around the world remain unclear or debatable (e.g., [50–52]). Therefore, it is essential to thoroughly analyze the characteristics of the overlying Cenozoic sediments, overpressure, and the tectonic stress background of basins to better understand the mechanisms that control the evolution of mud volcanoes and diapirs in the northern South China Sea. And it plays an important part in the exploration of oil and gas reservoirs and can be helpful to the exploration of natural gas hydrate in a sedimentary basin.

In this paper, the development characteristics of mud volcanoes and mud diapirs in the northern margin of the South China Sea were summarized by combining literature research and seismic profile interpretation. We analyze the

differences in the type and thickness of the Cenozoic sediments, tectonic stress, and lithostatic pressure (P) between the Yinggehai, Qiongdongnan, Pearl River Mouth, and Southwest Taiwan Basins and discuss influences of the overpressure, the thickness of sediments, and the stress on the formation process of piercement structures.

2. Geological Background

The northern continental margin of the South China Sea is located on the southeastern margin of the Eurasian megaplate. The geodynamic environment of this area is very complex due to the competitive influence of the Eurasian, Indian-Australian, and Pacific-Philippines Sea lithospheric plates and the opening of the South China Sea, among other factors [53–56]. The South China Sea has experienced multiple tectonic events, and its Cenozoic evolution is marked by an early Paleogene episode of continental fault depression and a late Neogene and Quaternary event of subsidence of marine facies. Furthermore, the northern continental marginal basin of the South China Sea has undergone rapid subsidence and sedimentation, giving rise to a thick Cenozoic sedimentary sequence characterized by high (fluid and lithostatic) pressure (P) and temperature (T) conditions in its lowermost parts.

There are many Mesozoic and Cenozoic sedimentary basins in the northern continental margin of the South China Sea including the Yinggehai, Beibu Gulf, Qiongdongnan, Pearl River Mouth, and Southwest Taiwan Basins [57]. The Yinggehai Basin is controlled by a strike-slip fault zone in the western margin of the South China Sea. The Qiongdongnan and Pearl River Mouth Basins are characterized by extensional rifting and uplift structures that were formed during the rift period. The Southwest Taiwan Basin, located at the edge of the South China Sea subduction and convergence zone, is controlled by lithospheric slab subduction and compressional faulting [58–61]. In the late Cenozoic (~5 Ma years ago), the continental marginal structure of the northern South China Sea was relatively stable, but the eastern margin of the South China Sea was strongly affected by the westward pushing Philippine plate. And the process of the strike-slip movement of the Red River Fault Zone affected the activity of the fault zone alongside the western margin of the study area [62].

The thickness of the sedimentary sequences over the northern continental margin of the South China Sea varies significantly (Figure 2). The thickness of the Cenozoic sediment is ~17 km in the Yinggehai Basin, whereas it may exceed 10 km in the deep-water area of the southern Qiongdongnan Basin. The Baiyun sag of the Pearl River Mouth Basin has a sedimentary sequence more than 10 km thick [49]. The thickness of the Cenozoic sedimentary rocks of the Southwest Taiwan Basin is 5 km on average and ~8 km at its maximum. The above-mentioned basins all have obvious formation overpressure, except the Pearl River Mouth Basin. Among them, the pressure coefficient in the central depression area of the Yinggehai Basin is basically greater than 2.0 and the pressure coefficient is 1.5~2.2 approximately in the center of the Qiongdongnan Basin and the depression

FIGURE 1: Distribution of mud volcanoes and mud diapirs in the northern margin of the South China Sea. Grey parts indicate mud diapirs of Yinggehai Basin (YGHB), Qiongdongnan Basin (QDNB), and Pearl River Mouth Basin (PRMB); grey triangles indicate mud volcanoes in the Dongsha Islands and Southwest Taiwan Basin (SW-TWB). Red lines indicate the location of seismic lines. Different colors (pink, yellow, and green) represent uplift, bulge, and depression areas, respectively (modified from [13, 49]). Black solid lines with numbers represent Cenozoic sediment thickness (modified from “Map of Cenozoic Sediment Thickness 1:2 000 000,” Atlas of geology and geophysics of the South China Sea, compiled by Guangzhou Marine Geological Survey); mud volcanoes and mud diapirs are found in areas of thick sediment.

center of this basin. These differences strongly affected the distribution and evolution characteristics of mud volcanoes and diapirs in each sediment basin of the South China Sea.

3. Research Approach

Guangzhou Marine Geological Survey (GMGS) and China National Offshore Oil Corporation (CNOOC) conducted extensive and detailed geophysical studies in the northern continental margin of the South China Sea. A large number of mud volcanoes and diapirs were recognized in the Yinggehai, Qiongdongnan, and Pearl River Mouth Basins on 2D and 3D seismic profiles and instantaneous frequency profiles (e.g., 25, 39, 43, 47–49). High-resolution multichannel 2D and 3D seismic datum we used below belong to the Guangzhou Marine Geological Survey (GMGS). In the course of geological and geophysical investigations, the seismic streamer was a Seal 24-bit digital cable produced by the Sercel Company in French. The cable was immersed in 8 m, and the air gun is immersed in 5 m. The channel number of a seismic streamer was 240, and the number of coverage is 60 times. The interval between receivers, shot interval, and the offset were 12.5, 25, and 175 m, respectively. The sampling rate was 1 ms, and the record length was 6 s. The frequency range of the original seismic data is 6 to 160 Hz, and the main frequency was about 75 Hz. GMGS processing datum is by the

GeoCluster 2.1 (CGG) processing system of French Geophysical Company. In addition, the instantaneous frequency profile can help to detect high attenuation areas such as free gas zones and gas chimneys [47]. Our datum and preexisting information on the type of fluid seepage structures in the aforementioned basins and the Southwest Taiwan Basin are used herein to discuss the distribution, genetic mechanism, and development characteristics of mud volcanoes and diapirs.

4. Results

Fluid seepage structures in mud volcanoes and diapirs frequently occur in Yinggehai, Qiongdongnan, Pearl River Mouth, and Southwest Taiwan Basins. Their distribution and evolution characteristics differ much among basins (Table 1). For instance, mud diapirs were recognized in the Yinggehai, Qiongdongnan, Pearl River Mouth, and Southwest Taiwan Basins. And most mud volcanoes occur in the Pearl River Mouth Basin, Southwest Taiwan Basin, and the Taiwan land [13, 39, 49, 63].

4.1. Characteristics of Mud Diapirs in the Yinggehai Basin. Mud diapirs in the Yinggehai Basin are the most typical of those found in the northern continental marginal basin of the South China Sea. Most of them are located in the central

FIGURE 2: Stratigraphic integrative column map of basins in the northern margin of the South China Sea (modified from [57]).

depression of the basin in five rows parallel to the long axis of the basin in the central uplift belt [25]. The largest covers an area of more than 700 km² and most others tens to hundreds of km² [25, 64]. The seismic profile shows that there are blank and cluttered anomalous seismic emission characteristics that are significantly different from the surrounding rock inside the mud diapir (Figure 3). Mud diapirs are developed in the Miocene stratum, piercing the T30 interface vertically and reaching the upper Yinggehai Formation. Mud diapir caused the “pull up” of the surrounding rock on both sides of it, and an upward arching phenomenon occurs on the top of the diapir.

4.2. Characteristics of Mud Diapirs in the Qiongdongnan Basin. Mud diapirs in the Qiongdongnan Basin are predominantly concentrated in the sedimentary center of the basin depression and in the deeper, thicker deposits in the transition zone of the sags and bulges of the basin (Figure 1). Diapirs are typically distributed in a NE direction at the deep-water area in the south and relatively concentrated in the Songnan low bulge and Lingnan low bulge areas [65]. Mud diapirs appear as vertically oriented or chimney-like structures on the seismic profiles, have some seismic anomalies such as clutter and blank inside them, and vary in sizes (Figure 4(a)). These blank or cluttered reflection signals

TABLE 1: Characteristics of mud volcanoes and mud diapirs in the northern South China Sea [25, 39, 43, 65–68].

	Scales	Distribution	Characteristics
Yinggehai Basin	Mud diapirs tens to hundreds of square kilometers, up to 700 km ² .	Primarily distribute in the central depression of the basin.	Mud diapir belts are arranged in a row of 5 rows of geese along the long axis of the basin.
Qiongdongnan Basin	Mud diapirs.	Predominantly concentrate in the sedimentary center of the basin depression and in the deeper, thicker deposits in the transition zone of the sags and bulges.	Mud diapirs varying in scale, structural style, and piercing layers. Mud diapirs are randomly distributed but occasionally occur in groups.
Pearl River Mouth Basin	Mud diapirs in Baiyun sag reach up to 8 km, and the largest one covers an area of 1000 km ² . Mud volcanoes in Dongsha islands have widths and heights of 0.5–2.0 km and 50–200 m.	Mud diapirs of Baiyun sag extend approximately NWW and are predominantly distributed in the southwestern part of the center of Baiyun sag. Many active mud volcanic belts were founded in the southwestern area of the Dongsha Islands.	Relatively concentrated distribution, generally consistent with the NWW fault system in the late Miocene, and the piercing layers are different. Mud volcanoes have characteristics of structural extrusion and are distributed in a SWW-NEE direction.
Southwest Taiwan Basin	94 mud volcanoes ranging in height from 65 to 345 m, with a pedestal diameter of approximately 680–4100 m. Mud ridges ranging from 3.9 to 56.5 km in length and 1.6 to 8.3 km in width.	Mud volcanoes and mud diapirs are primarily distributed in the deep waters of the southern depression of the basin.	Mainly distributed in the structural fault zone, mud volcanoes are mostly distributed on mud diapirs.

FIGURE 3: Seismic profile over the Yinggehai Basin. There are blank and cluttered anomalous seismic emission characteristics that are significantly different from the surrounding rocks. The mud diapir is developed in the Miocene stratum, piercing the T30 interface in a vertical column and reaching the upper stratigraphic layer of the Yinggehai Formation stratum. Above the top of the diapir, there is a phenomenon of upward arching of the stratum. Uplift of the mud diapirs caused the “pull up” of the surrounding rock on both sides.

exhibit lower instantaneous frequency values from deep to shallow on the instantaneous frequency profile, which is significantly different from the higher instantaneous frequency values of the surrounding rocks (Figure 4(b)). Owing to the upward migration of gas, some mud diapirs may give “pull-down” internal seismic reflection signatures (Figure 4(a)). The overlying strata of the mud diapirs are plastically arched owing to the puncturing effect of diapirism, resulting in the

formation and propagation of high-angle brittle faults and radially arranged fractures.

4.3. Characteristics of Mud Volcanoes and Diapirs in the Pearl River Mouth Basin. A large number of mud diapirs have been recorded in the Baiyun sag of the Pearl River Mouth Basin. The maximum intrusion height of mud diapirs in this area reaches 8 km, and the largest one covers a total area of

FIGURE 4: (a) Seismic profile over the Qiongdongnan Basin. Mud diapirs puncture into the Neogene strata in a vertical columnar or chimney-like form. Diapir intrusions caused arch-up deformation of the overlying strata and “uplift” of the wall layers. The interior of the diapirs is characterized by blank, clutter, bright spots and other abnormal seismic reflection characteristics. (b) Instantaneous frequency distribution map. The blank or cluttered reflection area presents a low instantaneous frequency from the deep to shallow part on the instantaneous frequency distribution profile, which is significantly different from the higher instantaneous frequency value of the surrounding rock.

~1000 km². Mud diapirs are mainly distributed in the southwestern side of the central part of the Baiyun sag (Zhuer depression) and extend ~NWW, which is generally consistent with the direction of the fault system developed in the late Miocene [65, 66]. The Shenhua area in the Baiyun sag of the Pearl River Mouth Basin displays typical diapiric structures. Mud diapirs are mainly developed in Paleogene strata pierced vertically through the T3 interface (Figure 5(a)). The tops of the mud diapirs reach the Miocene stratum, causing ductile arching of the overlying sedimentary layer. In addition, numbers of gas chimneys have been found in the Pearl River Mouth Basin. We can recognize two gas chimneys near the diapir in Figure 5(a). The left one shows pull-down continuous reflection inside while the right one shows pull-down and blank zone inside. Mud diapirs give lower instantaneous frequency values on the instantaneous frequency profiles (Figure 5(b)). Many mud volcanoes have

been found in the southwestern area of the Dongsha Islands, which distribute in a SWW-NEE direction, with single-mound widths of 0.5–2.0 km and heights of 50–200 m. There are more than 100-kilometer-wide mud volcanoes in the study area, and the largest one was 5 kilometers wide and 200 meters high [43, 67]. In the Dongsha Sea, the seismic profile reveals a thin Cenozoic sedimentary cover and the uplift of the Mesozoic basement caused the upward deformation of the overlying sediment (Figure 6).

4.4. Characteristics of Mud Volcanoes and Diapirs in the Southwest Taiwan Basin. Mud volcanoes and diapirs are widely distributed in the Southwest Taiwan Basin. Terrestrial mud volcanoes primarily occur in the hilly areas of southwestern Taiwan, whereas underwater mud volcanoes are mainly concentrated in the deep waters of the southern depression of the investigated basin and are characterized

FIGURE 5: (a) Seismic profile over the Shenhu hydrate exploration area in Baiyun sag of Pearl River Mouth Basin. One mud diapir and two gas chimneys can be recognized in the profile. Mud diapir developed in the Paleogene strata, with a vertical columnar piercing T3 interface and reaching the Miocene strata causing plastic deformation of overlying sediments. (b) Internal appearance of the mud diapir on the instantaneous frequency profile exhibiting a low instantaneous frequency.

by a larger size than that of their onshore equivalents [68]. A total of 94 submarine mud volcanoes have been reported from the Southwest Taiwan Basin and are subdivided into four sectors [69], with each mud volcano sector consisting of several mud volcanoes and most of them are located in fault zones [39, 68]. Based on a comprehensive analysis of multichannel seismic reflection (MCS) profiles, multibeam bathymetric data, and deep-towed sidescan sonar data, 10 NNE-SSW-oriented mud diapir ridges and 13 mud volcanoes which developed over these mud diapirs were identified in the Gaoping slope zone of the Southwest Taiwan Basin [39]. Some of these mud volcanoes and diapirs are still active [39, 70, 71]. The lengths of the mud diapir ridges vary from 3.9 to 56.5 km and their widths from 1.6 to 8.3 km [39]. They

range in height between 65 and 345 m, having a pedestal diameter of ~680 m to ~4100 m [19, 21, 39]. The fluid leakage structures in the Gaoping slope zone were formed during the Paleogene and its shallow strata of Paleogene age due to amplified intrusion of mud slurry exudates, gradually increasing the degree of expansion and piercing of the upper stratigraphic horizons of the investigated basin ([39], Figures 7 and 8).

5. Discussion

5.1. A Comparison of the Geological Aspects of the Investigated Piercement Structures. Mud volcanoes and diapirs in the continental marginal basins of the northern South

FIGURE 6: Seismic profile of the Dongsha Islands. The seismic profile reveals a thin Cenozoic sedimentary cover, and the uplift of the Mesozoic basement caused the upward deformation of the overlying sediment.

FIGURE 7: (a) Seismic profile and (b) the interpreted seismic profile over the Southwest Taiwan Basin. Five mud diapirs are present in this profile, and the two on the right have pierced through thick sediments and are exposed at the seafloor, and the surrounding rock is uplifted, obviously (modified from [39]).

China Sea are characterized by noteworthy differences in their distribution, morphology, and piercing horizon (Figure 9). Mud diapirs in the Qiongdongnan Basin are randomly distributed but occasionally occur in groups. In con-

trast, mud volcanoes and diapirs in the Southwest Taiwan Basin are distributed alongside the strike of deep faults and mud diapirs are arranged in 5 rows in an echelon pattern along the long axis of Yinggehai Basin. The largest mud

FIGURE 8: (a) Seismic profile and (b) the interpreted seismic profile of Southwest Taiwan Basin. Four mud volcanoes have developed on the mud diapir, and the surrounding rock is uplifted, mildly. Some fluid conduits can be noted on the profile (modified from [39]).

diapir in the Baiyun sag of the Pearl River Mouth Basin covers an area of $\sim 1000 \text{ km}^2$ and has a maximum intrusion height of $\sim 8 \text{ km}$ [66], and the largest mud diapirs in the Yinggehai basin covers an area of more than 700 km^2 . On the contrary, mud volcanoes distributed in the southwestern part of the Dongsha Sea have much smaller diameters ($0.5\text{--}2 \text{ km}$) and heights ($50\text{--}200 \text{ m}$; [43]). Furthermore, the size and piercing horizon of investigated fluid seepage structures also differ among the different basins or even within a single basin (Figure 9). For instance, the fluid leakage structures developed in the Southwest Taiwan Basin vary significantly in size, some of mud diapirs within the basin with only a few meters of punctured but others pierce through shallow sedimentary formations and even close to the seafloor [39]. In the Yinggehai Basin, invasive activity pierces the T40-T30 seismic reflection interface in the Dongfang district (Figure 3), whereas mud diapirs almost penetrate the T14 seismic emission interface in the Changnan district [49].

Despite the differences among the mud volcanoes and diapirs in the continental marginal basins of the northern South China Sea, some interesting similarities exist between the investigated piercement structures and other typical mud volcano and diapir occurrences from elsewhere. For example, the distribution of mud volcanoes along the Berca-Arbanasi zone in Romania is controlled by a large anticline structure and the distribution of mud volcanoes along the Pede-Apennine margin in Italy is controlled by a thrust fault [9, 72]. In a similar way, most of mud volcanoes and diapirs in the Yinggehai, Qiongdongnan, Pearl River Mouth, and Southwest Taiwan Basins are structurally controlled by regional fault systems, just like mud diapirs in Yinggehai Basin, Baiyun sag (Table 1), and mud volcanoes along the Gutingkeng anticline and Chishan Fault [73], except mud volcanoes distributed in the southwestern part of the Dongsha Islands in the Pearl River Mouth Basin.

FIGURE 9: (a) Developmental pattern of mud diapirs in Yinggehai Basin. Mud diapirs developed based on the sediments from the Neogene Sanya Formation to Yinggehai Formation. Mud diapirs vertically pierce through to the Quaternary strata. The grey-purple part indicates the Paleogene stratum. The source of MD-1 and MD-5 is deeper than other mud diapirs, and MD-1 pierces the shallower stratum; the sources of MD-2, MD-3, and MD-4 are shallow, and they pierce through strata at different depths. (b) Developmental pattern of mud diapirs in Qiongdongnan Basin. Mud diapirs are derived from Paleogene (Eocene-Oligocene) shale, which penetrates the Neogene strata vertically. The grey-purple part indicates the Paleogene stratum. The source of MD-1 and MD-3 is deeper than other mud diapirs, and MD 1 pierces the shallower stratum; the sources of MD 2 and MD-4 are shallow, and they pierce through strata at different depths. (c) Developmental pattern of mud diapirs in Baiyun sag of Pearl River Mouth Basin. The source of the diapir material is Paleogene (Eocene-Oligocene) shale, and diapirs pierce the Neogene strata vertically. The grey-purple part indicates the formation below the T50 interface. The source of MD-1 and MD-4 is deeper than other mud diapirs, and MD-1 pierces the shallower stratum; the sources of MD-2, MD-3, and MD-5 are shallow, and they pierce through strata at different depths. (d) Developmental pattern of mud volcanoes and mud diapirs in Southwest Taiwan Basin. The source of mud volcanoes and mud diapirs is Neogene (Miocene and Pliocene) shale, and the fluid penetrates through the Quaternary strata or the seafloor. The grey-purple part indicates the Paleogene stratum. MV-1 and MV-2 represent mud volcanoes of different scales; MD-1 indicates the shallow diapir of the source, and the vertical piercing is close to the seabed; MD-2 and MD-3 have deeper sources and pierce through different horizons.

Piercement structures in the northern continental marginal basin of the South China Sea predominantly occur in deep-water areas covered by thick sediment (Figure 1). From west to east, the mud volcanoes and diapirs are distributed in the central depression, the deep-water areas of the southern depression, in the Baiyun sag, the deep-water areas of the southwestern of the Dongsha Islands, and the deep-water areas in the southern depression of the basin. This may be related to the high temperature and overpressure caused by the rapid subsidence and later hydrocarbon generation in deep-water areas covered by sedimentary sequences of substantial thickness.

5.2. The Influence of Overpressure on the Formation Process of Piercement Structures. The Cenozoic sedimentary sequences hosted in the marginal basins of the South China Sea show evidence of rapid subsidence and sedimentation. These thick Cenozoic sediment sequences contributed to the establishment of high T and overpressure conditions in the investigated marginal basins.

More specifically, the Yinggehai Basin is characterized by a high sedimentation-deposition rate which is conducive to the development of overpressure in the Paleogene and Neogene strata. The central mud diapir belt was generated under strong overpressure and has a large formation pressure coefficient. The formation pressure coefficient of most areas in the Yinggehai Basin is above 2.0, and the biggest formation pressure coefficient in the central mud diapir belt can reach to 2.28 (Table 2). Moreover, geophysical and geochemical studies suggest that the source of mud diapirs in the Yinggehai Basin may be the Neogene Sanya Formation to the bottom of the Yinggehai Formation [49, 68], which is equivalent to the position of the initiation of overpressure in the Yinggehai Basin. Seismic profiles also reveal that the puncture layer of mud diapirs in the Yinggehai Basin encompasses Neogene to Quaternary strata.

In the Qiongdongnan Basin, the geothermal gradient is high and overpressure is generally developed in the central part of the basin and the central depression in the southern side of the basin [62, 74]. The anomalous overpressure in the central depression is mainly developed in mudstones of the Paleogene to Meishan Formation of Miocene, with a pressure coefficient of 1.5–2.2 [75]. Geophysical and geochemical evidences suggest that the source material of mud diapirs/mud volcanoes in the Qiongdongnan Basin is most likely consists of shales in Eocene and Oligocene [49], which is equivalent to the position of the initiation of overpressure in the Qiongdongnan Basin. Seismic profiles reveal that the diapir puncture layer in the Qiongdongnan Basin encompasses Paleogene to Neogene strata.

Neotectonic movements since the late Miocene have obliterated any signs of extremely high P in most areas of the Pearl River Mouth Basin. However, low-overpressure still exists in the deep-water areas of the southern slope of the basin [76]. Overpressure simulation analysis carried out by Shi et al. [76] revealed that during the sedimentary evolution of the Baiyun sag, overpressure was only 9.0 MPa, which may not be high enough to drive the flux of fluids in the Baiyun sag. Geological and geochemical studies suggest that the

source material of mud diapirs in the Pearl River Mouth Basin may be Eocene and Oligocene argillite [49]. Furthermore, seismic profiles reveal that mud diapirs in the Baiyun sag intruded the overlying strata up to the level of the Quaternary sedimentary layer (like mud diapirs in Shenhu hydrate exploration area (Figure 5(a))).

The Southwest Taiwan Basin has undergone a long period of compression. The large amount of terrigenous clastic material coupled with the high sedimentary filling rate in the Southwest Taiwan Basin resulted in a rapid deposition of fine-grained materials of Miocene to Pliocene shales. And undercompaction resulted by high filling rate, coupled with the genesis of hydrocarbons, finally led to the formation of an abnormal high T and overpressure environment, providing a significant source of muddy material and energy for the formation of mud volcanoes and diapirs in Southwest Taiwan Basin. Geophysical and geochemical investigations suggest that the source material of mud diapirs and mud volcanoes in the Southwest Taiwan Basin was most likely Miocene and Pliocene argillite, penetrating the overlying strata up to the level of Quaternary sediments to form mud volcanoes.

In conclusion, the distribution of mud volcanoes and diapirs is closely related to the distribution of overpressure in the basin, except in the Pearl River Mouth Basin.

5.3. Controls on Variations in the Type and Mode of Piercement Structures. The genesis of mud volcanoes and diapirs in the northern continental margin of the South China Sea is generally controlled by quite similar geological processes. Consequently, the question arises as to what causes the different geological modes of occurrence of the investigated piercement structures. The reasons for this difference are most likely the following: (1) variations in the regional tectonic setting, leading to a different stress status in each basin, and (2) variations in the type and thicknesses of the sediment filling each basin, and difference of overpressure.

In general, most mud volcanoes and diapirs are formed in accretionary wedges, some occur in extensional settings, and a few are linked to both convergent and divergent environments [39]. The formation and evolution process of the Yinggehai Basin is controlled by the NW strike-slip Red River Fault Zone, and mud diapirs distributed in the central depression area are in the form of en echelon along the NW axis of the basin. The formation of the Qiongdongnan and Pearl River Mouth Basins was mainly controlled by extensional rifting and uplift structures formed during the rift period, among which the Pearl River Mouth Basin is controlled by the dextral tensional-torsional environment in the Early Cenozoic [62]. A series of NWW-oriented strike-slip faults are produced within the Baiyun sag [49] consistent with the distribution of mud diapirs/volcanoes. And the genesis and evolution history of the Southwest Taiwan Basin are largely controlled by a subduction-related reverse fault system. The distribution of mud volcanoes in the Southwest Taiwan Basin and the southwest part of Taiwan Island is obviously related to the distribution of the strike-slip fault or anticline [77]. Consequently, mud diapirs distributed in the Yinggehai Basin may be related to strike-slip tectonism,

TABLE 2: Characteristics of the Yinggehai Basin, Qiongdongnan Basin, Pearl River Mouth Basin, and Southwest Taiwan Basin in the northern South China Sea [43, 57, 65, 67, 76].

	Sediment thickness of Cenozoic	Characteristics of overpressure	The age of the source layers
Yinggehai Basin	The maximum deposition thickness of Tertiary and Quaternary in the central depression exceeds 17000 m.	Overpressure is generally developed in Tertiary, and the pressure coefficient* in most areas of the central mud diapir belt is more than 2.0, and the maximum is 2.28.	Neogene Sanya Formation to the bottom of the Yinggehai Formation
Qiongdongnan Basin	The Cenozoic sediment thickness is up to 11000 m. The maximum thickness of Paleogene and Neogene is over 7000 m and 3000~5000 m, respectively.	The overpressure is generally developed in the center of the basin. The pressure coefficient* of the central depression in the deep-water area in the south, Ledong-Lingshui sag, and Songnan sag reaches 1.5-2.2, over 2.2, and 2.0, respectively.	Eocene and Oligocene
Pearl River Mouth Basin	The maximum thickness of Cenozoic is over 10000 m, of which the maximum thickness of Paleogene, Neogene, and Quaternary is over 6000 m, 3500 m, and less than 400 m, respectively. Dongsha area is characterized by thin (~0.5 km) Cenozoic sediments and thick (up to 5 km) Mesozoic strata.	The abnormal overpressure has disappeared in most areas, and only a small overpressure exists in marine mudstone strata below the continental slope and deep source rock strata. The maximum overpressure once possessed by Baiyun sag is only 9.0 MPa.	Eocene and Oligocene Mesozoic
Southwest Taiwan Basin	The Cenozoic thickness of the northern depression and southern depression is 5000-7000 m and generally 5000 m, respectively, and the maximum thickness of the sedimentary center near Kaohsiung is more than 10000 m.	Abnormal high temperature and overpressure are develop in the basin.	Miocene and Pliocene

*Formation pressure coefficient (α_p) = formation pressure (P_p)/hydrostatic pressure (P_h), α_p of YGHB and QDNB refer to [49, 75], respectively.

mud diapirs in the Qiongdongnan and Pearl River Mouth Basins may be linked to an extensional geotectonic regime and in Southwest Taiwan Basin, and mud volcanoes and diapirs may be linked to a strike-slip and compressional setting. According to the distribution and scale of mud volcanoes and diapirs mentioned above and previous research results [39], the extrusion background and strike-slip stress may be of key importance to the genesis of mud volcanoes and diapirs, but differences in stress field do not directly lead to the difference in the scale of mud volcanoes or diapirs (Table 1, mud diapirs in Yinggehai or Southwest Taiwan Basins are not larger than those in the Pearl River Mouth Basin), and the trends of tectonic (such as faults) in these basins can affect the distribution of mud volcanoes and diapirs.

Thick Cenozoic sediments are generally deposited in the deep-water area of the northern South China Sea, which commonly show characteristics of rapid subsidence and sedimentation. These fine-grained sediments of Cenozoic are presumed to comprise the essential material for the genesis of mud volcanoes and diapirs [49, 68]. The material sources of mud diapirs in the Yinggehai Basin are mainly mud shale of Miocene and Pliocene, but the source layers of mud volcanoes or diapirs in the Qiongdongnan Basin and Pearl River Mouth Basin are Eocene and Oligocene mud shale [49]. Particularly, geochemical and isotopic analysis shows that fine-grained and loose sediments of Mesozoic age provided the essential sources for the genesis of mud volcanoes in the Dongsha area [43]. Furthermore, thick Miocene and Pliocene marine shales and argillites probably provided the geological

material for the formation of diapiric structures in the Southwest Taiwan Basin [49]. We conclude that source materials of the fluid seepage structures in the investigated sedimentary basins were of similar lithology but were derived from different stratigraphic horizons.

The thickness of the sedimentary sequence of a basin may affect the formation of piercing structures to some extent (we used drilling datum to calculate the average depth of the source layer of mud volcanoes/mud diapirs in Yinggehai, Qiongdongnan, Pearl River Mouth, and Southwest Taiwan Basins in Table 2). For basins filled with thick sedimentary, it may require more power to move fluids along a fracture to the surface (physical simulation results of our research group can verify it (unpublished)). Assume that there are two sets of formations with similar pressure and the heights of the intrusion are the same, for areas where we have a thinner deposition thickness, mud may travel to the surface to form mud volcanoes. In contrast, in areas covered by thick sediment deposits, mud diapirs may be formed. The study of the seismic profiles of mud diapirs (with multiple periods of activity) from the Qiongdongnan Basin and of mud volcanoes (superimposed on mud diapirs) from the Southwest Taiwan Basin indicates that fluid intrusion-related activities can pierce shallower sediments or even giving rise to the formation of mud volcanoes if the fluid penetrates the seabed [39].

Compared to other basins in the northern continental margin of the South China Sea, the Yinggehai Basin is characterized by relatively significant overpressure of the

sedimentary strata and affected by large-scale strike-slip faults. However, this basin hosts a large number of mud diapirs instead of mud volcanoes, which may be attributed to a thick Cenozoic sedimentary sequence. Due to the deposition of thick Quaternary sediments on thick Neogene mud shales, it becomes more difficult for fluids to invade the seafloor to form mud volcanoes. For the Southwest Taiwan Basin, with analogous overpressure status and stress background to those of the Yinggehai Basin, it is likely that a relatively thin Cenozoic sedimentary cover favored the genesis of mud volcanoes. From the seismic profiles mentioned above (Figures 3–6), it can be found that mud diapirs and mud volcanoes are formed by the upward migration of deep fluids into the overlying strata, and the difference between them is only whether they reach to the seafloor or the surface and accumulate to form a mound structure. We can regard mud diapir as the intermediate link of the formation process of mud volcano. Therefore, we do not rule out the possibility of the formation of mud volcanoes in the Yinggehai Basin after multiple diapir activities.

Overall data indicate that the extrusion background and strike-slip stress may be of key importance to the genesis of mud volcanoes and diapirs, but differences in stress field do not directly lead to the difference in the scale of mud volcanoes or diapirs. The thickness of the sedimentary cap (above the mud source layer) and the existence of deep faults in a geological basin also play a fundamental role in determining the type of the ensuing piercing structure.

5.4. The Factors Controlling the Genesis of Fluid Leakage Structures. The genesis of mud volcanoes has been the subject of many frontline studies and remains a hotly debated issue among geologists, many of whom passionately defend theories about the formation of such piercing structures. Briefly, two elements are essential for the genesis of a mud volcano; namely, thick muddy strata with high pore-fluid P (overpressure) and substantial power required to enable mud volcanic eruption (i.e., seismic activity; [78–80]). Zhang [49] carried out a detailed investigation on the formation conditions and genetic mechanisms of mud volcanoes and diapirs in the northern continental margin of the South China Sea. He concluded that the genesis of piercing structures in the Yinggehai, Qiongdongnan, and Southwest Taiwan Basins and the Baiyun sag of the Pearl River Mouth Basin is primarily controlled by the establishment of a high T and overpressure environment, suitable tectonic stress, sufficient supply of mud, and a well-developed fracture system.

By the reasoning in the foregoing paragraph, it is inferred that regional tectonic, sedimentary sequence, and overpressure are of central importance in the formation of fluid seepage structures. In particular, faults in the central depression of the Yinggehai Basin are not very extensive, but local overpressure is significant. The Pearl River Mouth Basin is generally characterized by extensional rifting. However, low overpressure is remarked only in a small area. Overpressure is moderate in the Qiongdongnan Basin. Among them, faults are not well-developed in the Ledong-Lingshui sag with high and widespread overpressure (overpressure characteristics of

these basins are recorded in Table 2), but faults are widely developed in the Changchang sag with local and weak overpressure [75]. The Pearl River Mouth Basin has been affected by neotectonic movements, abnormally high P has disappeared, and the overpressure in the Baiyun sag during the sedimentary evolution of the Pearl River Mouth Basin has been estimated to be only 9.0 MPa [76], which is not sufficient to drive diapiric activities. Nevertheless, the large number of mud diapirs in the Pearl River Mouth Basin indicates that extremely high pore-fluid P may not be the only driving force for the formation of fluid seepage structures in the region. A system of NWW-striking fractures most likely aided the formation of diapiric structures in the Baiyun sag area.

Mud volcanoes are not true volcanoes as they do not produce lava and are not associated with igneous activity. Since mud volcano systems and magma systems have similar mechanisms and are controlled by similar processes [9, 81, 82], a mathematical model developed to quantify the eruption mechanism of a magmatic volcano may be quite useful for understanding the commencement, buildup, and operation of a mud volcano as well. Cheng et al. [83] used a numerical model to apply the finite element and finite difference methods, to study the effects of magma viscosity, effective density difference, and depth on minimum overpressure (minimum magma chamber pressure required for magma migration to the surface). He concluded that an increase in the tectonic stress and effective density difference of the vertical fault plane can reduce the minimum overpressure and the minimum overpressure will increase due to an increase in magma viscosity and model depth.

These results have significant implications for the mechanisms that control the formation of mud volcanoes or diapirs. More specifically, the depth of a mud source layer, the regional tectonic stress, and physical properties of the mud itself can affect the process of moving mud slurry to the surface. If the depth of the mud source layer (thickness of sediment), the stress, and physical properties of the mud itself are constant, fluid will rise to the surface to form a mud volcano once the overpressure of the mud source layer becomes greater than the minimum overpressure required to move the slurry to the surface (Figure 10). If overpressure is less than the minimum overpressure, the mud slurry will intrude the overlying layers without reaching the surface. In this case, a mud diapir will be produced. This is in agreement with the notion we discussed above that the thickness of a sediment affects the type of the fluid leakage structure that will be formed. A deep-seated mud source layer requires a larger minimum overpressure to form mud volcanoes, favoring the formation of a mud diapir. In contrast, for a thin sediment sequence, small pressure will be required in the mud source layer giving rise to a mud volcano.

The multiphase mud diapir/volcanic activity presented on the seismic profile reflects the process of “release-accumulation-release” of energy (overpressure) in the source layer. During the upward movement of the piercing structure-forming fluid, the P decreases and this leads to the cessation of intrusion activity. When energy accumulation reaches a high level and tectonic activity occurs, energy

FIGURE 10: Pattern diagram of the formation mechanism of mud volcanoes and mud diapirs. (a) Stratigraphic profile of mud volcanoes and mud diapirs. MD-1, MD-2, and MD-3 are mud diapirs, which puncture through different layers, and the source layers of MD-1 are shallower than MD-2 and MD-3. MV-1 and MV-2 are mud volcanoes, and the source layers of MV-2 are deeper than MV-1. (b) Internal structure diagram of MV-2, Z is the depth of the source, $\Delta\sigma_z$ is the tectonic stress, P is the overpressure in mud reservoirs, and ρ_s and ρ_m are the densities of the surrounding rock and mud, respectively.

is released and the fluid starts rising again through a network of open fractures. When the mud source layer is under high P conditions, the fluid can be transported up to the seabed to form a mud volcano. If not, mud diapir will be formed. Therefore, the existence of a thick Cenozoic sedimentary sequence in the Yinggehai Basin most likely permitted the formation of mud diapirs instead of mud volcanoes. In contrast, the relatively thin sedimentary sequence in the Southwest Taiwan Basin led to the genesis of mud volcanoes.

By the reasoning in the foregoing paragraphs, it is concluded that tectonic stress, the thickness of sediment, and regional faulting are factors that exert significant control over the type of the resultant piercing landform.

6. Conclusions

The fluid leakage structures cropping out on the seafloor of the sediment basins hosted in the northern continental margin of the South China Sea show significant variations in their morphological and structural characteristics. Differences in stress field do not directly lead to the difference in the scale of mud volcanoes or diapirs. Overpressure is not the only energy for the formation and evolution of mud diapirs/volcanoes; fractures may play an important role in this process. The thickness of the sediment has a strong impact on the formation of fluid leakage structures that thicker sediment is more conducive to the development of mud diapirs and the thinner one is more likely to form mud volcanoes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The findings achieved herein are solely the responsibility of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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