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Research Article

Formation Mechanism of Mud Volcanoes/Mud Diapirs Based on Physical Simulation

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The formation of mud volcanoes/mud diapirs is directly related to oil and gas accumulation and gas-hydrate mineralization. Their eruptive activities easily cause engineering accidents and may increase the greenhouse effect by the eruption of methane gas. Many scholars have performed much research on the developmental characteristics, geochemistry, and carbon emissions of mud diapirs/mud volcanoes, but the formation mechanism of mud diapirs/mud volcanoes is still controversial. Mud diapirs and mud volcanoes are especially developed in the northern South China Sea and are accompanied by abundant oil, gas, and gas-hydrate resources. Based on the mud volcanoes/mud diapirs in the northern South China Sea, the physical simulation experiments of mud diapir/mud volcano formation and evolution under different fluid pressures and tectonic environments have been performed by loading a fluid-input system in traditional sandbox simulation equipment. The genetic mechanism of mud diapirs/mud volcanoes is revealed, and a fluid-leakage model of mud diapirs/mud volcanoes under different geological conditions is established. We believe that in an overpressured environment, the greater the thickness of the overlying strata is, the greater the pressure or power required for the upward migration of muddy fluid to penetrate the overlying strata. Tectonic activity promotes the development of mud volcanos/mud diapirs. To a certain extent, the more intense the tectonic activity is, the more significant the effect of promoting the development of mud volcanoes/mud diapirs and the larger the mud diapirs/mud volcanoes become.

1. Introduction

Mud diapirs and mud volcanoes are two kinds of geological phenomena caused by the upward migration of deep fluid under overpressure that penetrates the overlying strata. If mud fluid is ejected from the surface or seafloor, mud volcanoes are formed; otherwise, mud diapirs are formed. The submarine mud diapirs and mud volcanoes have the same genetic mechanism and similar evolutionary characteristics and can even be considered as the late evolution product of the mud-diapir structure [1–6].

Mud volcanoes have been found in more than 40 land areas and more than 20 sea areas in the world, and at present, more than 2000 mud volcanoes have been found [7–9]. The mud diapirs/mud volcanoes in the northern continental margin basins of the South China Sea are mainly distributed in the central mud diapir belt of the Yinggehai Basin in the shallow water area of the continental shelf, the central and southern depression belts of the Qiongdongnan Basin in the deepwater area of the continental slope, the Baiyun Sag of the Zhu II Depression in the Pearl River Mouth Basin, the southeastern Dongsha Sag, and the deepwater area of the southern sag of the Southwest Taiwan Basin, as well as some adjacent onshore areas.

Submarine mud diapirs and mud volcanoes are important indicators for exploring deepwater oil and gas hydrates

[10–14]. They can be used as a channel for gas-hydrate sources. Furthermore, a large amount of methane emitted from them will cause greenhouse effects and climate change [1, 15, 16]. Mud volcanoes are also significant signs of modern crustal movements and neotectonic activities. The activity of mud diapirs and mud volcanoes affects oil and gas drilling and pipeline laying, which may cause engineering accidents. When they occur on the continental margin, they are prone to cause slope instability and damage to submarine infrastructures [17, 18]. Davies et al. believe that drilling destroys the underground rock structure and causes mud to gush out [19]. Normile believes that the impact of drilling on underground structures is too weak to trig mud volcanoes [20]. Zoporowski and Miller point out that there are still doubts about whether the epicenter of the earthquake, which is far from the mud volcano, can break the rock stratums hundreds of meters away [21].

At present, there are many studies on mud diapirs/mud volcanoes, mainly based on geochemical tests and analyses of ejecta (natural gas, sediment, and water) [4, 22], supplemented by field geological structural analysis and geophysical interpretation. Some scholars have also performed numerical simulations of the eruption process of mud volcanoes and the relationship between oil/gas leakage from mud volcanoes and hydrate accumulation [20, 21, 23, 24]. However, the formation mechanism of mud volcanoes/mud diapirs, especially their triggering factors, remains unresolved. Whether they are formed by diapirism of deep overpressured fluid penetrating the overlying strata and breaking through the surface or seafloor by extrusion, by strike slip, or by extension of deep muddy fluid ejecting along the fault or triggered by other factors such as seismic activity remains controversial [9, 18, 25–27].

Based on previous studies on the formation mechanism of mud diapirs/mud volcanoes and by reasonably controlling the variables (tectonic stress, fluid pressure, sedimentary environment, etc.), we perform physical simulation experiments of the formation mechanism of mud diapirs/mud volcanoes under action mechanisms and analyze the influence of overpressured fluid activity, tension, strike slip, and other geological processes on the eruption of mud volcanoes/mud diapirs. Finally, we establish a dynamic model of the development of mud volcanoes/mud diapirs and discuss the formation mechanism of submarine mud volcanoes/mud diapirs.

2. Geological Background

The Zhongjiannan Basin, Yinggehai Basin, Pearl River Mouth Basin, and Qiongdongnan Basin are well-developed areas of mud volcanoes or mud diapirs in the northern South China Sea (Figure 1).

Under the influence of plate collision, central basin expansion, and fault zone activities in the western margin of the South China Sea, the Zhongjiannan Basin finally formed a strike-slip extensional composite basin under the transformation of tensile and shear stresses [28]. Since the Middle Miocene, the basin was in a compressional and torsional stress environment [28]. Cenozoic strata are widely developed in Zhongjiannan Basin, with a thickness of 500-8500 m [29]. The basin has gone through rift and postrift subsidence stage, in which the semideep marine deep sea sediments had a higher deposition rate [30]. Rapid sedimentation and undercompaction lead to overpressure in the deepwater area of the basin while the high geothermal gradient in the basin provides good conditions for deep hydrocarbon generation [31].

The Qiongdongnan Basin is influenced by the South China Sea expansion, the Red River fault strike slip and the Pacific plate movement [32–34]. In the neotectonic stage, the stress field around the basin changed significantly [35]. Affected by the double effects of the right lateral strike slip of the Red River fault zone and the subduction of the Pacific plate, the Qiongdongnan Basin formed a tectonic pattern of west extension and east compression [35]. Finally, a double-layer structure of "lower fault and upper depression" in Qiongdongnan Basin was formed under the background of extension [36]. The maximum Cenozoic sedimentary thickness of the basin can reach 11000 m, and the Quaternary sedimentary rate can reach 2 mm/y, with a thickness of more than 2000 m [29] with large geothermal gradient and widely developed overpressure strata [36]. The strong overpressure areas are mainly distributed in the central depression of the deepwater area in the south of the basin [36], and the pressure coefficient is 1.5-2.2 [37].

Yinggehai Basin is a typical strike-slip extensional Cenozoic sedimentary basin, which is controlled by the double mechanisms of mantle lithosphere extension and Red River fault strike slip [38]. The thickest Cenozoic strata in Yinggehai Basin can reach 17 km [39]. The high sedimentation rate and rapid accumulation in the basin resulted in the undercompaction of Cenozoic sediments, coupled with high temperature and hydrocarbon generation of organic matter [39]. Due to the influence of diapirism, the overpressure surface in the central mud diapiric zone of the basin is shallow and the formation pressure coefficient is large [40]. The formation pressure coefficient in most areas of the central mud diapir belt in the central depression is greater than 2.0, and the maximum formation pressure coefficient can reach 2.28 [40]. The thick Cenozoic sediments and widespread overpressure in Yinggehai basin have laid a good foundation for the development of mud diapirs.

The Pearl River Mouth Basin was influenced by the subduction and compression of the Pacific plate, the collision between South China and Indosinian block, and the expansion of the South China Sea since Cenozoic, which was in a dextral extensional and torsional environment in the early Cenozoic [30]. The whole basin of Pearl River Mouth Basin is developed with extremely thick Cenozoic strata and locally developed residual Mesozoic strata [29]. The basin as a whole is characterized by rapid subsidence and rapid sedimentary filling with the Cenozoic sedimentary thickness of Baiyun Sag up to 10 km [41], but the Cenozoic sedimentary filling in the southwest sea area of Dongsha uplift is very thin (estimated to be 0.8 km at most) [42]. However, the Mesozoic sedimentary filling is relatively thick (the estimated maximum thickness is more than 5000 m), and fine-grained sediments such as shale are developed [6]. The abnormal high temperature and overpressure in the basin are mainly

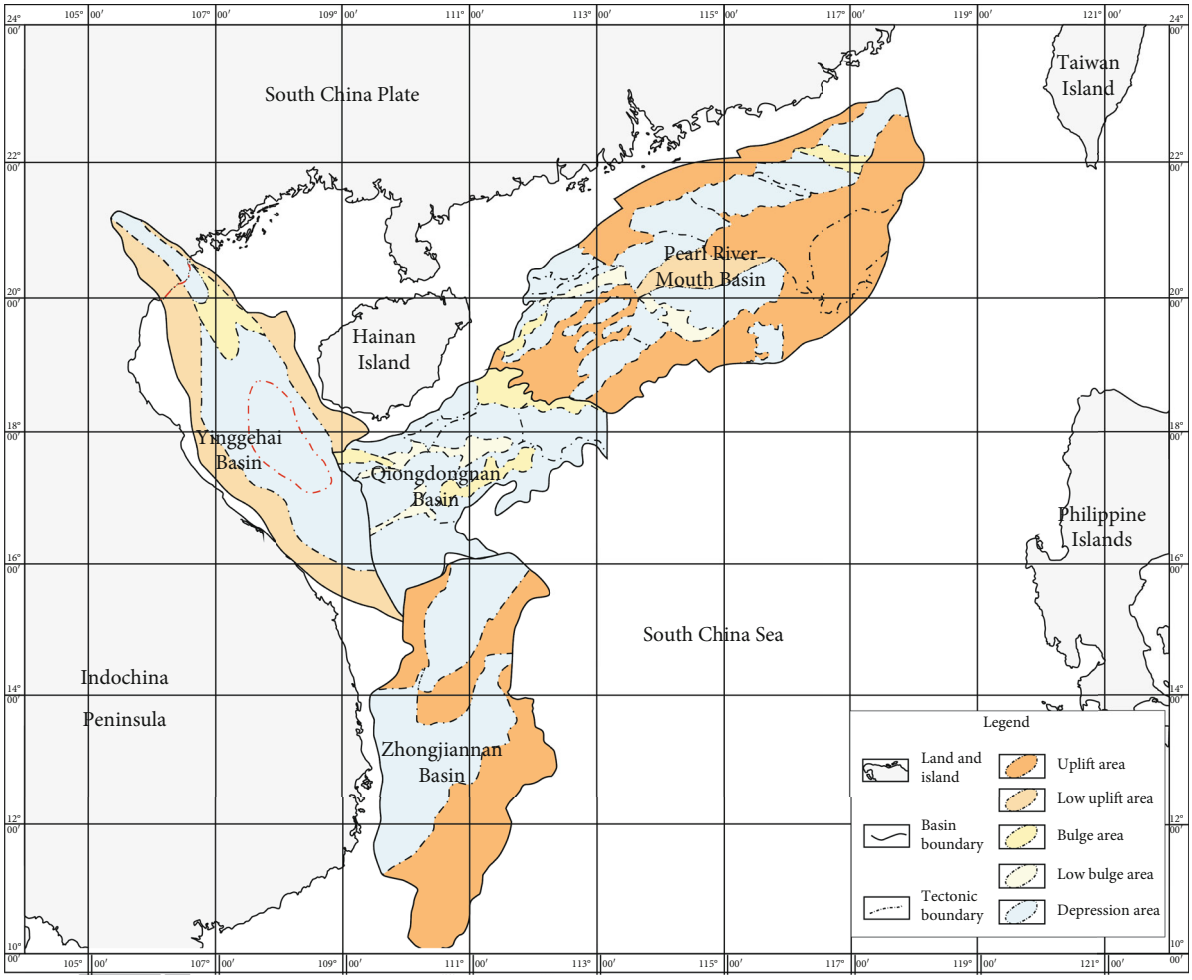

Figure 1: Study area distribution map (modified from Zhu et al.) [30].

distributed in the deepwater area of the southern slope, but it has disappeared in most areas because of the influence of neotectonic movement since the late Miocene [43]. The results of pressure simulation analysis show that the maximum overpressure developed in Baiyun Sag during the sedimentary evolution of the Pearl River Mouth Basin was only 9.0 MPa [44].

3. Experimental Methods

3.1. Establishment of Mud Diapir/Mud Volcano Geological Model. Due to the differences in tectonic geological background and provenance conditions, the distribution and quantity of mud diapirs and mud volcanoes in the Yinggehai Basin, Pearl River Mouth Basin, Qiongdongnan Basin, and Zhongjiannan Basin are distinctly different. Under the background of a strike-slip extensional structure in the western part of the northern South China Sea, the Yinggehai Basin, which is rich in mudstone-material bases and has high-temperature and overpressured dynamic conditions, is extremely developed with mud diapir structures. Mud volcanoes are widely developed in the northern part of the Zhongjiannan Basin, which is also located under a strike-slip extensional background in the western part of the northern South China Sea [28]. Moreover, the Qiongdongnan Basin and the Pearl River Mouth Basin under the background of extensional tectonic stress have a good provenance foundation, but the mud volcanoes/mud diapirs and other fluid-leakage structures in the Qiongdongnan Basin with more developed faults and overpressure are not more developed than those in the Pearl River Mouth Basin, and a large-scale mud volcano is also found in the southwestern area of Dongsha in the Pearl River Mouth Basin (Figure 2) [45–47].

Therefore, according to the geological background of the basin, four models of overpressure, tension, strike slip, and transtension are set up to simulate the formation of mud diapirs and mud volcanoes. The pressure condition is firstly taken as an independent variable, so the influence of pressure on the formation condition of mud volcanoes is explored by changing the formation thickness. The purpose of setting the extensional, strike-slip, and transtension formations is to explore the influence of tectonic activities on the formation of mud diapirs or mud volcanoes. We need a control group not affected by tectonic activities, so the overpressure group also acts as a control group.

3.2. Establishment of Mud Diapir/Mud Volcano Physical Model. The basic theory of physical simulation experiments

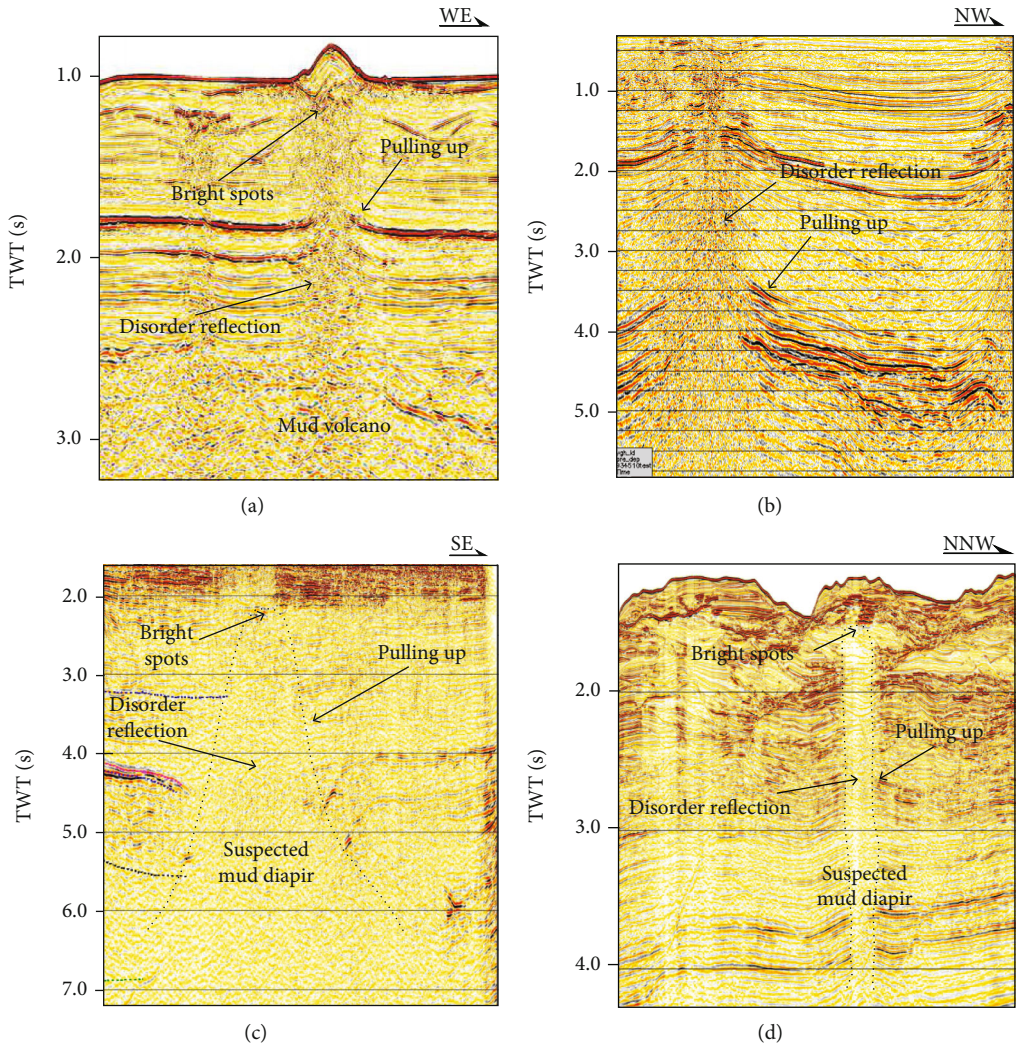

Figure 2: Four seismic profiles of mud diapirs in the northern basins of the South China Sea: (a) seismic reflection characteristic of mud diapirs developed in Zhongjiannan Basin; (b) seismic reflection characteristic of mud diapirs developed in Yinggehai Basin; (c) seismic reflection characteristic of suspected mud diapir in Qiongdongnan Basin; (d) seismic reflection characteristics of mud diapirs developed in Shenhu area, Pearl River Mouth Basin.

is the similarity principle. Based on the similarity principle, an experimental model is established, and the entire geological structural movement is regarded as a mechanical system [48–51]. The successful development of the physical simulation of salt structures and magma intrusion and its mature technology is of great significance for reference, which provides an effective guarantee for mud volcano simulation [48–51]. In recent 20 years, based on the new results of rock mechanics experiments, the new experimental materials and new simulation methods have been used to simulate the salt structure in almost all the geotectonic environments [52–55]. Corti et al. introduced the flowing propanol liquid between materials simulating the lower crust and upper mantle, successfully revealing the influence of mantle melting and magma underplating on deformation during lithospheric extension [56]. Sun et al. introduced high-viscosity silicone into the model to simulate rigid block, which effectively reflected the influence of lithospheric lateral heterogeneity on deformation [57].

This experiment uses a set of improved sandbox, physical simulation, and experimental equipment (Figure 3). The equipment has an operating platform, four constant speed steering motors, and two movable bottom plates. It is composed of a fluid reservoir, a pressure pump, a fluid-pressure recorder, and an operating platform. Driven by the motor, the operation boards of the device can realize uniform movement in all directions to simulate crustal movement and to simulate various tectonic activities, such as tension, strike slip, and transtension. When the fluid-input system is connected to the bottom of the sandbox platform, the formation of diapirs can be simulated by injecting fluids with different viscosities under certain pressure conditions.

3.3. Experimental Materials and Parameters. Quartz sand and watered clay are the two most commonly used experimental materials in sandbox and physical simulation experiments. The main lithologies of the four basins in the northern

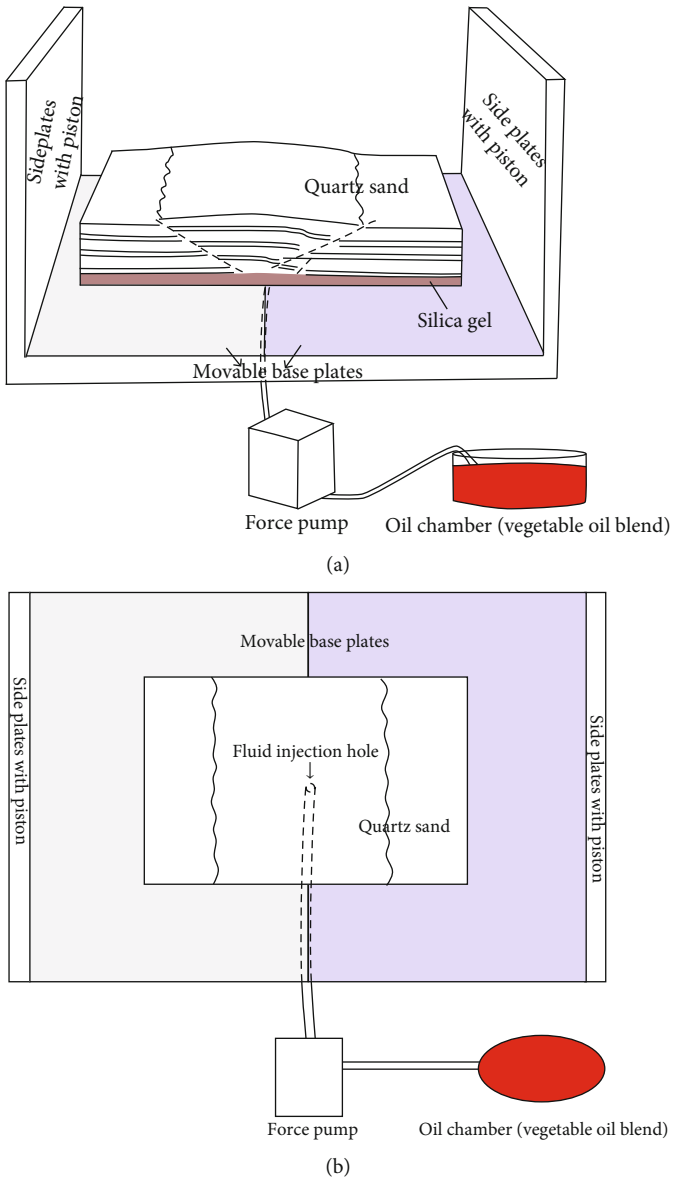

Figure 3: A typical sandbox simulation experiment device: (a) stereogram of the device; (b) plane figure of the experiment device.

South China Sea are mudstone and siltstone. Combined with the principle of similarity, a silica-gel mixture (silica gel mixed with a certain amount of quartz sand) was used to simulate the formation of a plastic basement. A channel for upward fluid migration was reserved in the plastic silica-gel substrate. Eighty-mesh and 60-mesh quartz sands were used to simulate mudstone and siltstone, respectively. During the laying process, the two kinds of quartz sand were alternately laid to simulate the interbedded state of the mudstone and siltstone in the actual formation. A very thin layer of 80-mesh brown quartz sand was laid between each pair of layers as an indicator layer to better display various stratum deformations under different tectonic-stress backgrounds. The mixture of vegetable oil and silt was used to simulate the deep fluid. The specific experimental material parameters are as follows (Table 1).

The experiment was performed under normal gravity conditions. According to the basic law of kinetic similarity, the similarity ratio between the model and the prototype is calculated as follows (Table 2).

During the process of the physical simulation experiment, the formation and evolution of mud diapirs/mud volcanoes in the northern basin of the South China Sea were simulated by controlling the quartz-sand thickness, fluid-injection pressure, and tectonic-stress background of the model to reveal the influence of the geological-stress background, basin sedimentary characteristics, and tectonic characteristics on the formation and evolution of mud diapirs/mud volcanoes. The formation mechanism of mud diapirs/mud volcanoes in these Cenozoic basins in the northern South China Sea is discussed.

4. Results

4.1. Physical Simulation of Mud Diapir/Mud Volcano Formation under Overpressure. The formation process of

Table 1: Parameters of experimental materials.

Materials	Simulation object	Parameters
Silica-gel mixture	Plastic mantle	Viscosity: 10^4 Pa·s Density: approximately 1.2 g/cm^3 (at 28°C)
80-mesh quartz sand	Mudstone	Particle size: 180 μm Internal friction angle: 31°-38° Density: approximately 2.2-2.65 g/cm^3
60-mesh quartz sand	Siltstone	Particle size: 250 μm Internal friction angle: 36°-40° Density: approximately 2.2-2.65 g/cm^3
Vegetable oil mixture	Fluid injection	Viscosity: 10^2 Pa·s Density: approximately 1.6 g/cm^3 (at 28°C)

Table 2: Parameters of experimental materials.

Parameters	Physical model	Geological model	Similarity ratios
Length	1 cm	1 km	1×10^5
Density	1.35 g/cm^3	2.3 g/cm^3	0.6
Gravity acceleration	9.8 m/s^2	9.8 m/s^2	1
Cohesion	20-90 Pa	10×10^4 Pa	2×10^{-6}~9×10^{-4}
Viscosity	5×10^4 Pa·s	1.7×10^{19} Pa·s	3×10^{-15}
Time	1 h	0.23 ma	5×10^{-10}
Displacement velocity	0.0005-0.001 mm/s	0.8-1.6 mm/y	2×10^4

Table 3: Experimental parameters and record results of the overpressured group.

Experiment type	Serial number	Model size (cm × cm)	Nature of base	Material of overlying strata	Thickness of overlying strata (mm)	Displacement of tension (mm)	Displacement of strike slip (mm)	Pressure (MPa)
Overpressure	1-1	25 × 25	None	Dry quartz sand	78	—	—	0.30
	1-2	25 × 25	None	Dry quartz sand	104	—	—	0.40

mud diapirs/mud volcanoes under an overpressured background was simulated by injecting fluid controlled by a pressure pump, and different lithologic formations were simulated by white quartz sand with different particle sizes. By controlling the viscosity of the fluid, formation lithology, and other unrelated conditions and by changing the thickness of the formation, we designed three different thicknesses of overlying strata for the experiments and obtained a series of corresponding relationships between formation thickness and the pressure required for fluid injection (Table 3).

The thickness of the overlying strata in experiment 1-1 was 78 mm, and the pressure required for fluid ejection was 0.3 MPa (Figure 4). The thickness of the overlying strata in experiment 1-2 was 104 mm, and the pressure required for fluid ejection was 0.4 MPa (Figure 5). When the model was cut from the outside to the inside, it could be observed that the depth of stratum deformation increased, distinct diapirism appeared in the most central part, and the upward traction of stratum was very obvious.

4.2. Physical Simulation of the Formation Process of Mud Diapirs/Mud Volcanoes under the Background of Tension and Strike Slip. We set up a tension group and strike-slip group for comparative experiment. In the tension experiment, the two operating boards were laterally displaced at the speed of 30 mm/h, and the left and right boards were tensioned at the same distance. In the strike-slip experiment, the thickness of the formation, fluid viscosity, fluid pumping pressure (the pressure was kept at 0.3 MPa), and other conditions were consistent. Only the displacement direction was changed to explore the size and shape characteristics of mud diapir formation under different formation movement conditions. The data are as follows (Table 4).

During the tensile process, the surface of the model gradually exhibited a symmetrical fracture. With increasing tensile displacement, the fracture became more obvious (Figure 6). After the lateral cutting of the model, clear stratigraphic faults could be seen at the edge, and a diapiric structure appeared in the center. The stratum was punctured by fluid and pulled upward.

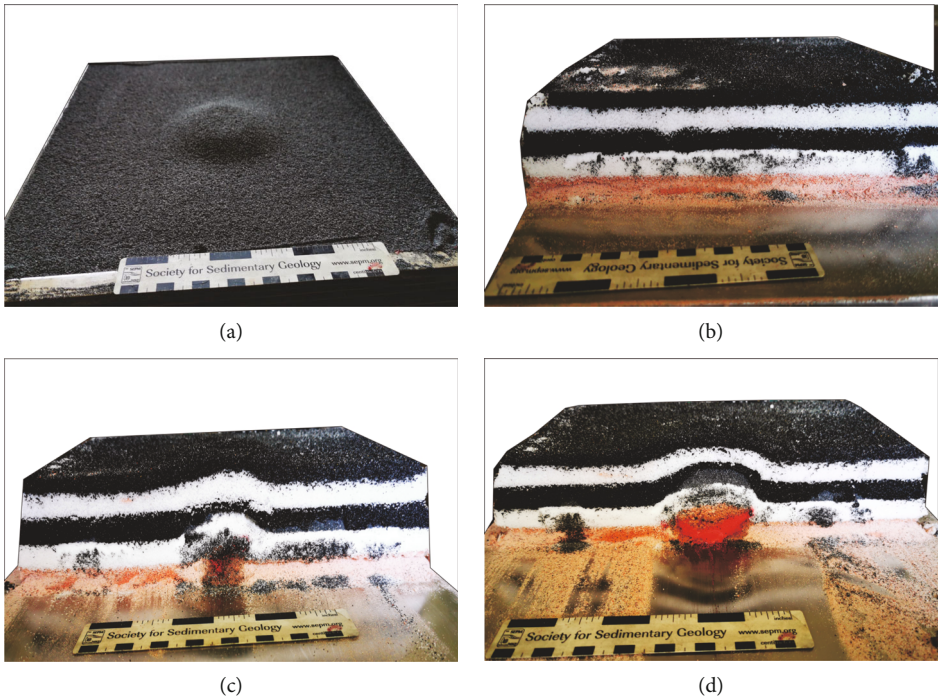

Figure 4: Experiment 1-1 records the formation simulation of mud diapir under overpressure. (a) After fluid injection, the model surface forms a mound like uplift; (b) the side view of the model; (c) the crosscutting diagram of the model outer edge, which shows that under the action of fluid arching, the stratum appears to be upward bending; (d) the crosscutting diagram of the model center, which shows that the stratum is faulted and pulled upward under the action of diapir.

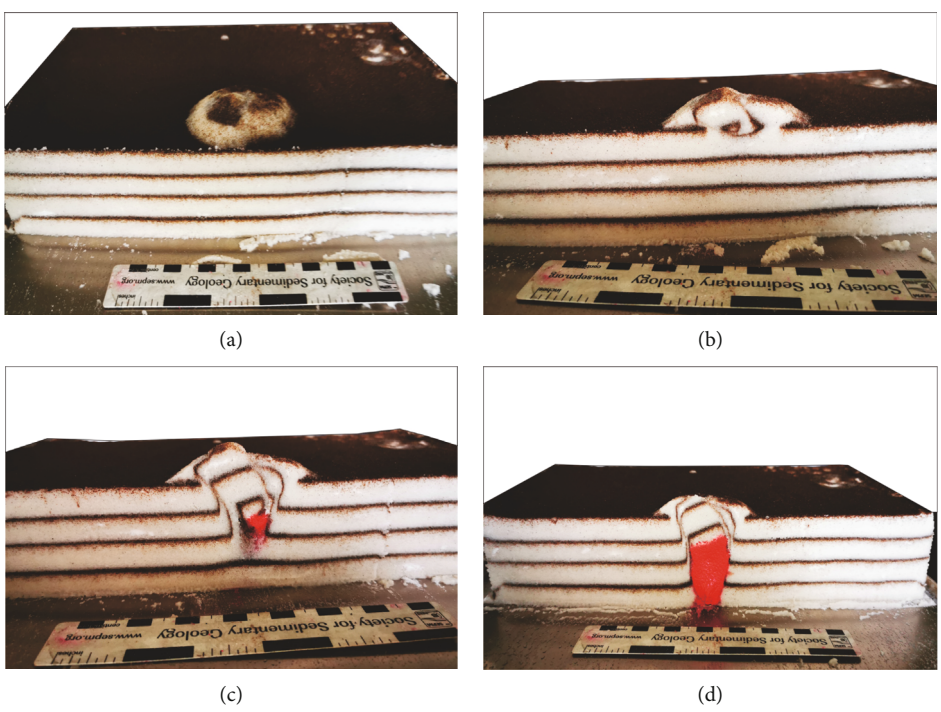

Figure 5: Experiment 1-2 records the formation simulation of mud diapir under overpressure. (a) After fluid injection, the model surface forms a mound shaped uplift; (b) the side section of the model shows the formation fold deformation inside the mound shaped uplift; (c) the cross section of the model outer edge shows that under the action of fluid arching, the formation appears to have an upward bending deformation; (d) the cross section of the model center shows the formation fault puncture under the action of diapir, and the formation on both sides appears to have an obvious fold deformation upward traction.

Table 4: Experimental parameters and record results of the tension and strike-slip group.

Experiment type	Serial number	Model size (cm × cm)	Nature of base	Material of overlying strata	Thickness of overlying strata (mm)	Displacement of tension (mm)	Displacement of strike slip (mm)	Pressure (MPa)
Tension	2	25 × 25	Plastic basement	Dry quartz sand	104	40	—	0.30
Strike slip	3	25 × 25	Plastic basement	Dry quartz sand	104	—	40	0.30

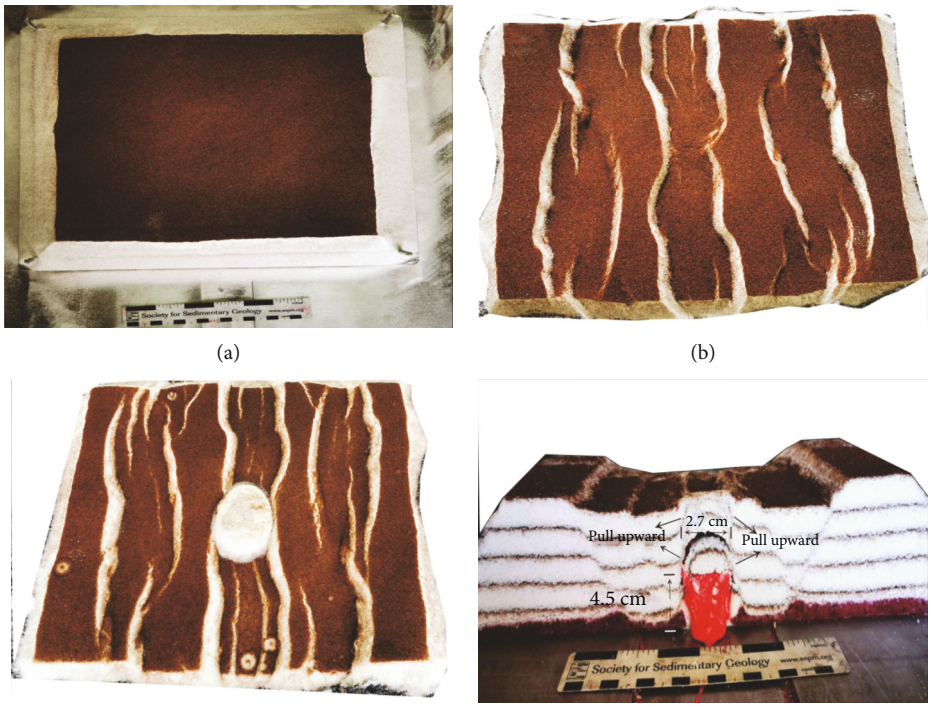

Figure 6: Experiment 2-1 records the formation simulation of mud diapir under the tension background. (a) In the early stage of tension, there are a few fractures on the surface of the model. (b) In the late stage of tension, there are a lot of symmetrical fractures on the surface of the model. (c) In the crosscutting diagram of the outer edge of the model, it can be seen that there are mounds in the middle of the model and a lot of symmetrical fractures on the side. (d) In the crosscutting diagram of the center of the model, the fluid flows up and punctures the stratum, and the stratum is pulled upward.

In the process of strike slip, an inclined fracture gradually appeared in the center of the model surface. With the gradual increase in the degree of strike slip, several small symmetrical fractures gradually appeared on both sides of the central large fracture (Figure 7). After the lateral cutting of the model, though formation faults could be seen, only a slight diapir activity was observed, and the scale of diapir was much smaller than that of experiment 2.

4.3. Physical Simulation of the Formation of Mud Diapirs/Mud Volcanoes under the Background of Transtension. The vertical and longitudinal movements of the two operation boards were controlled simultaneously to create the background of transtension. In the 30° transtension group, the tension on both sides was 25 mm, the strike slip was 43 mm, the total tension was 50 mm, and the strike slip was 86 mm; in the 60° transtension group, the tension on both sides was 43 mm, the strike slip was 25 mm, the total tension was 86 mm, and the strike slip was 50 mm. The tension speed was set at 30 mm/h, and the strike-slip speed was set at 40 mm/h. The other conditions were the same as those in experiments 2 and 3, and only the transtension angles of the two batches were changed. The experimental results are as follows (Table 5).

Experiment 4 used a 25 mm tensile displacement and 43 mm strike-slip displacement; therefore, the transtension angle was 30 degrees. During the experiment, with the progress of tension and strike slip, the model was gradually twisted and deformed, a symmetrical fracture appeared on the surface of the model, and obvious uplift appeared on the surface after fluid injection (Figure 8). The diameter of this mud diapir was about 2.4 cm, and its height was 6.9 cm. Experiment 5 used a 43 mm tension displacement and 25 mm strike-slip displacement; therefore, the transtension angle was 60 degrees (Figure 9). The diameter of the mud diapir was about 3.3 cm, and its height was 7.1 cm. The deformation of this group of experiments was more severe, and the size of the diapir was larger.

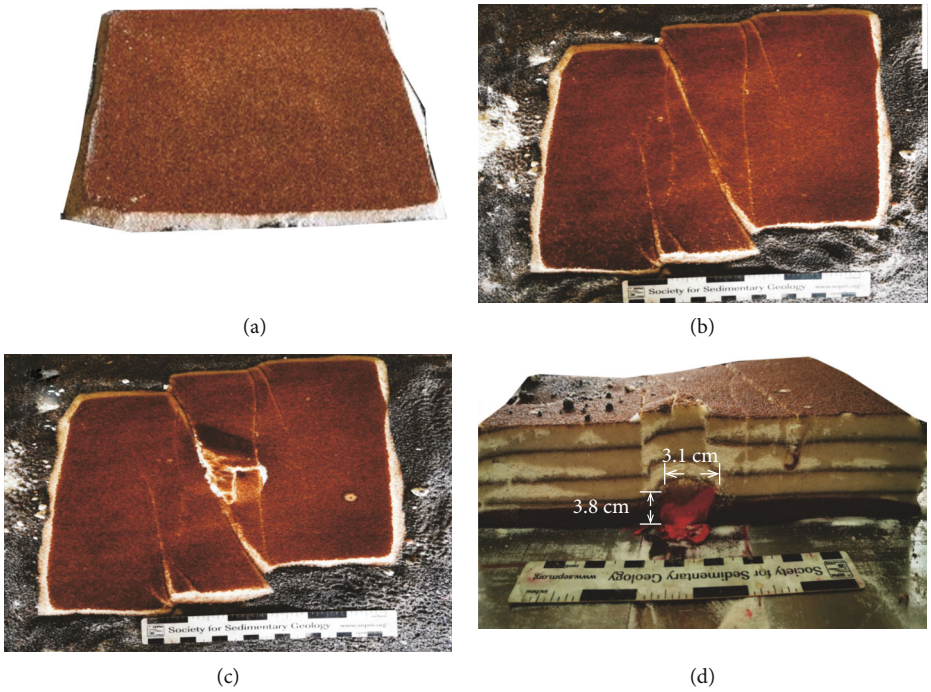

Figure 7: Formation simulation of mud diapir under the background of strike slip. (a) Plane photo of the strike-slip formation model; (b) completion of strike slip, symmetrical fracture of the model; (c) after injection of fluid, mound-like uplift appeared on the model surface, and the formation was punctured and fractured; (d) cross section in the center of the model, formation fault could be seen, but only a slight diapir activity was observed, and the scale of diapir was much smaller than that of experiment 2.

Table 5: Experimental parameters and record results of the transtension group.

Experiment type	Serial number	Model size (cm × cm)	Nature of base	Material of overlying strata	Thickness of overlying strata (mm)	Displacement of tension (mm)	Displacement of strike slip (mm)	Pressure (MPa)
30° transtension	4	25 × 25	Plastic basement	Dry quartz sand	104	50	86	0.30
60° transtension	5	25 × 25	Plastic basement	Dry quartz sand	104	86	50	0.30

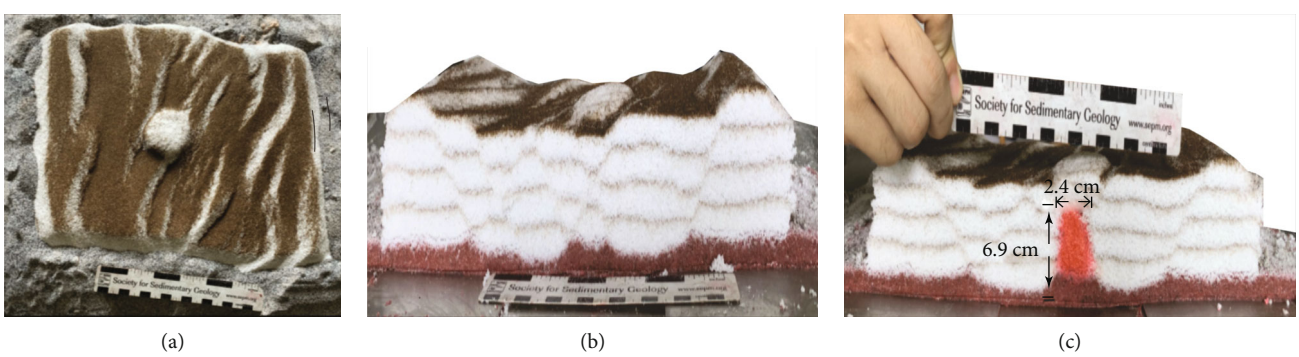

Figure 8: Simulation of formation of mud diapir in the background of 30° transtension. (a) More serious deformation of the model occurs in the background of 30° transtension, and a large number of fractures appear on the surface of the model; (b) lateral view of the outer edge of the model, which shows the undulation and deformation of the stratum, forming fractures; (c) central lateral view of the model, seeing a diapir upwell and punctured stratum.

5. Discussion

5.1. Effect of Pressure on the Formation of Mud Volcanoes/Mud Diapirs. In the overpressure group experiment, we changed the formation pressure by changing the thickness of the overlying strata and simulated the pressure required for fluid upwelling to form mud diapirs/mud volcanoes. The experimental results show that under the same

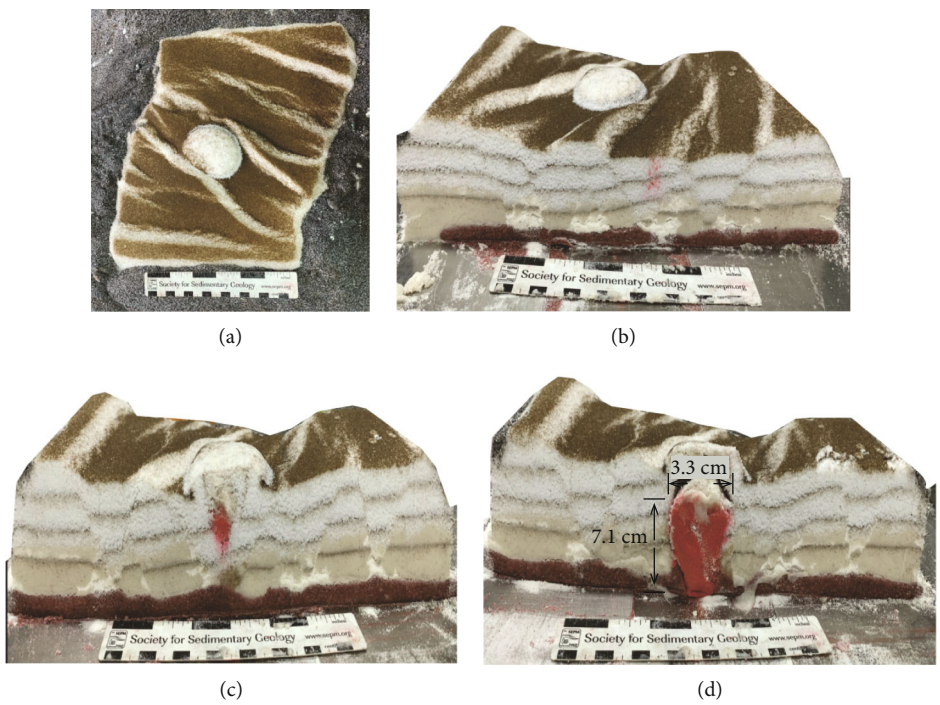

Figure 9: Formation simulation of mud diapir under 60° transtension. (a) Under the action of 60° transtension, the model appears to have distortion and deformation, resulting in symmetrical fracture; (b) side section of the model, science and technology mound-shaped uplift and a large number of fractures under the action of transtension; (c) side section of the model mound-shaped uplift edge, fluid outlet, stratum puncture, and upward traction deformation; (d) side section of the model center, seeing the diapir upwell and punctured stratum.

unrelated conditions, such as fluid viscosity and lithology, the greater the thickness of the formation was, the greater the pressure required for fluid ejection during the formation of mud diapirs.

In the actual geological environment, the main factors affecting formation pressure are mainly reflected in two aspects: the depth of the fluid source and the thickness of the sedimentary cover overlying the mud-source layer. When the depth of the fluid source is deeper or the sedimentary cap on the mud-source layer is thicker, the pressure/power is greater that is required for the upward migration of the fluid to penetrate the overlying strata and to finally reach the seabed to accumulate and form mud volcanoes. In an environment of high temperature and high pressure, deep fluid easily produces plastic flow and migrates upward, forming mud diapirs or mud volcanoes through the stratum [41, 58]. Therefore, in the process of the formation of mud diapirs and mud volcanoes, the pressure on the deep thick undercompacted plastic material has a crucial impact on the formation of mud diapirs and mud volcanoes.

An obvious evidence for this process is that the Zhongjiannan Basin and the Yinggehai Basin have similar geodynamic backgrounds, and the fluid thermodynamic conditions of the Yinggehai Basin are better than those of the Zhongjiannan Basin, even though the hydrocarbon-generation conditions are better [28–31, 38–40]. However, the fluid-leakage structure in the Yinggehai Basin is mainly characterized by a large-scale mud diapir structure and a lack of mud volcano structure, while there are more mud volcanoes and mud volcano groups in the northern Zhongjiannan Basin [28]. Previous studies have shown that the thickness of Cenozoic strata in Yinggehai Basin is up to 17 km, while that in Zhongjiannan Basin is 500-8500 m [29, 39]. Therefore, the sedimentary thickness of Yinggehai Basin is much thicker than that in Zhongjiannan Basin, which may be the reason for the lack of mud volcano structure in Yinggehai Basin. Combined with the physical simulation experiment, the overlying sedimentary cap rock of Yinggehai Basin increases the pressure threshold of upward migration of deep fluid, which is not conducive to upward migration of fluid, so that the basin mainly forms mud diapir structure and less mud volcano structure [41]. The difference in the development of mud diapirs/mud volcanoes between the Zhongjiannan Basin and Yinggehai Basin confirms the importance of overpressure to the development of mud diapirs/mud volcanoes.

5.2. Influence of Tectonic Activity on the Formation of Mud Volcanoes/Mud Diapirs. Tectonic activities often lead to strata movement, such as ascending and descending, spreading and colliding, and strike slip. Unfortunately, due to the limitation of experimental conditions, we did not simulate the formation process of mud volcanoes/mud diapirs under the condition of strata ascending and descending. In four groups of tension, strike-slip, and transtension experiments, we simulated strata movement by controlling the longitudinal and vertical movement of the platform and simulated the tectonic activity of different intensities by changing the displacement of these movements.

Compared with the over-pressured groups, we find that the formation with fluid breakthrough caused by tension

and strike-slip background was higher, and the fluid-injection volume was larger under the same conditions of pressure, formation lithology, fluid-injection velocity, and fluid viscosity. Moreover, the fluid-injection volume caused by tension was much larger than that caused by strike slip. It indicated that the effect of strike-slip condition on fluid migration was not as good as that of tension. The fault system formed by strike slip had a poor migration effect on deep fluid. Under the same conditions, the scale of mud diapir formation under 60° transtension was larger than that under 30° transtension, and the fluid transgression breakthrough was higher. To some extent, it indicates that the more intense the tectonic activity is, the more favorable it is to promote the development of mud volcanoes/mud diapirs [17, 18].

The explanation for this pattern is that when tectonic activity occurs, it is often accompanied by strata moving perpendicular to or along the section or both. This leads to the formation pressure relief and the formation of faults, which makes it easier for deep fluids to migrate upward through the faults and to form mud volcanoes/mud diapirs. In the transtension experiment, the increase in extensional or strike-slip displacement corresponds to the intensification of tectonic activity; the greater the strata pressure relief is, the larger the faults formed, which is more conducive to the formation of mud diapirs/mud volcanoes, and the larger the scale of the faults. On the other hand, the faults formed under the tension condition are often larger than those under the strike-slip condition. The stratum is mainly subjected to tensile stress under tension conditions and shear stress under strike-slip conditions. Therefore, the tension environment is more suitable for the development of mud volcanoes/mud diapirs than the strike-slip environment. Compared with the strike-slip background, the formation thinning caused by tension can make the formation scale of mud diapirs larger and the uplift deformation of overlying strata more obvious. We speculate that the pressure threshold of the diapir formation is reduced by the uplift and thinning of strata and that the extensional tectonic setting affects the upward migration process of deep fluid, resulting in differences in the shape and scale of the fluid-leakage system.

The abnormal high pressure in most areas of the Pearl River Mouth Basin has disappeared, and only a small overpressure exists in the marine mudstone strata below the continental slope and deep-source rocks. The maximum overpressure in the Baiyun Sag was only 9.0 MPa [58], which may not be enough to induce the development of mud volcanoes or mud diapirs. It is speculated that a large number of mud diapiric structures developed in the Zhu II Sag may be due to the extensive development of extensional faults, which provide a good channel for upward migration of deep fluid and reduce the pressure threshold for upward migration of deep fluid penetrating the overlying strata to form diapiric structures. This further indicates that the extensional environment is more conducive to the development of mud diapirs/mud volcanoes.

In the experiments of tension and strike-slip groups, during the formation of mud diapirs, most of the fluid upwelled vertically, and a small amount of fluid intruded upward along the formed fault, which in turn contributed to the further expansion of the original fault. In the transtension group experiment, due to the effect of external pressure, most of the fluid directly broke through the formation and upwelling from the center of the model, and only a small part migrated upward along the fault formed by transtension. But in the experiment of strike-slip formation, we could see the obvious lateral migration of fluid.

The Zhongjiannan Basin and Yinggehai Basin mentioned above were affected by both strike-slip and extensional stresses during their evolution (Figure 10). Shear faults or extensional structures are widely developed in these basins. It is speculated that under an extensional strike-slip stress background, the strike-slip faults or extensional faults formed in the early stage of basin evolution provide a better migration channel for the upward migration of mud diapirs, while the extensional and torsional structures formed in the late stage of basin evolution mainly cause the lateral migration of mud-source materials but may not develop into a dominant channel.

Combined with the results of physical simulation experiments, it can be inferred that the faults formed by extensional or strike-slip tectonic activities can provide channels for the upward migration of deep fluid, thus effectively reducing the energy required for the formation of mud diapirs and mud volcanoes, especially the pressure caused by the extrusion of surrounding rock on fluid [26, 27]. This is consistent with the genetic mechanism of mud diapir/mud volcano structures emphasized by experts and scholars such as Kopf [4]. To a certain extent, the strike and shape of the faults affect the size and morphology of the mud diapirs and mud volcanoes. On the other hand, in the small faults near the main fault, the squeezing effect caused by the intrusion of fluid further expands these small faults and increases the complexity of the fault system.

5.3. Discussion on the Formation Mechanism of Mud Diapirs/Mud Volcanoes. We think that there are two main genetic mechanisms of mud diapirs and mud volcanoes:

(1) Under a condition of rapid deposition, fine-grained sediments accumulate to form an undercompacted environment, while under the condition of high heat flow, an overpressured environment is formed, resulting in the upwelling of deep fluid material and the formation of mud diapirs or even mud volcanoes

In addition, thinner strata are more conducive to the formation of mud diapirs/mud volcanoes. This may explain why the Yinggehai Basin, which has a favorable mud-source material basis and dynamic conditions, has developed a large-scale mud diapir structure and lacks a mud volcano structure, while the northern Zhongjiannan Basin, which has a similar geodynamic and sedimentary geological background, has developed more mud volcanoes and their groups.

When the stratum is thin, the slender mud diapir indicates a greater upward migration velocity of fluid; when the stratum is thick, the base of the mud diapir is wider and the height is smaller, indicating that there is a process of fluid

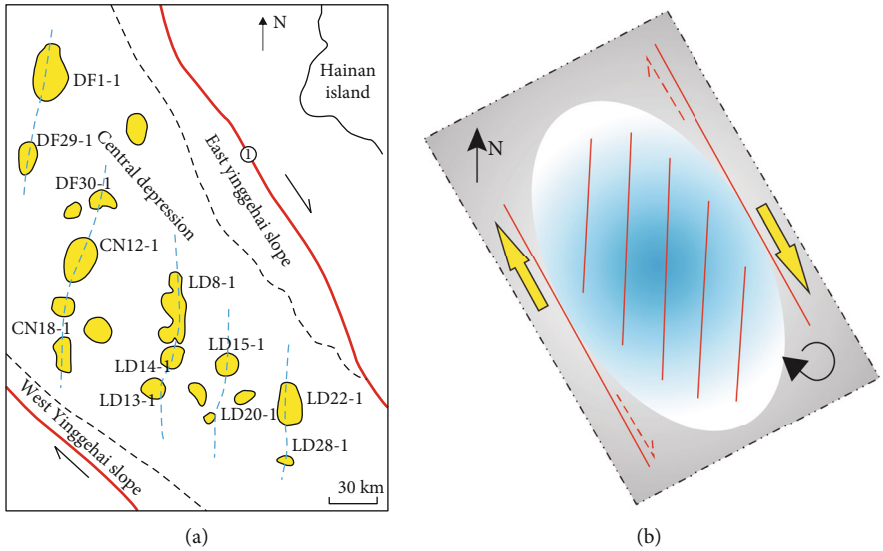

Figure 10: (a) Distribution map of mud diapirs in the Yinggehai Basin; (b) a model of strike-slip environment in Yinggehai Basin.

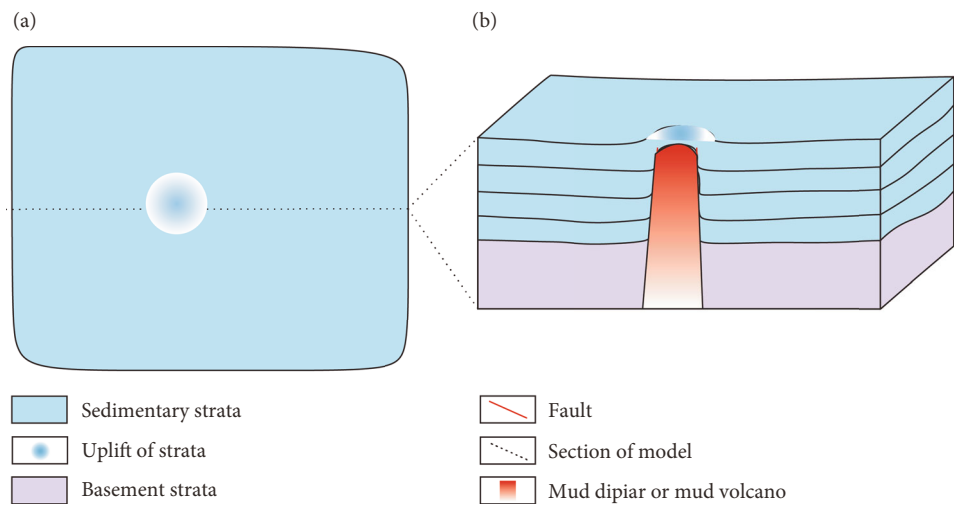

Figure 11: Development mechanism model of mud diapirs/mud volcanoes under simple overpressure background. (a) The top view of the strata after the development of mud diapirs/mud volcanoes under overpressure background. It can be observed that a stratigraphic uplift is on the position where mud diapir or mud volcano develops. (b) Three-dimensional map of the development mechanism of mud diapirs/mud volcanoes under overpressure background. The strata around mud diapirs/mud volcanoes are almost vertical faulted, the strata at the development position of mud diapirs/mud volcanoes are obviously pulled up, and the top strata are uplifted.

accumulation in the early stage of mud diapir formation. Combined with the results of overpressure group experiment, we simulated the development mechanism of mud diapirs/mud volcanoes under simple overpressure environment (Figure 11). It can be seen that the strata around mud diapirs/mud volcanoes are almost vertically staggered, the strata at the development position of mud diapirs/mud volcanoes are obviously pulled up, and the top strata are uplifted.

(2) The fault channel formed by tectonism can reduce the pressure required for the formation of mud diapirs/mud volcanoes, can provide a channel for the migration of deep mud-source materials, and can lead to the formation of mud diapirs and mud volcanoes

Under the same pressure conditions, tectonic activity leads to a larger scale of mud diapirs and higher penetration formation. Even in the absence of overpressure in the Pearl River Mouth Basin, there are still many mud diapiric structures in the Zhu II Sag of the Baiyun Depression. This indicates that east-west, north-northeast, and northwest-trending faults in the basin may provide a good channel for the upward migration of deep fluid to form mud diapirs, thus reducing the pressure threshold required for the development of mud diapirs.

We have simulated the development mechanism of mud diapirs/mud volcanoes in tension environment and tension torsion environment, respectively, in Figures 12 and 13. It can be found that different tectonic activities will change the development form of mud diapirs/mud volcanoes. In

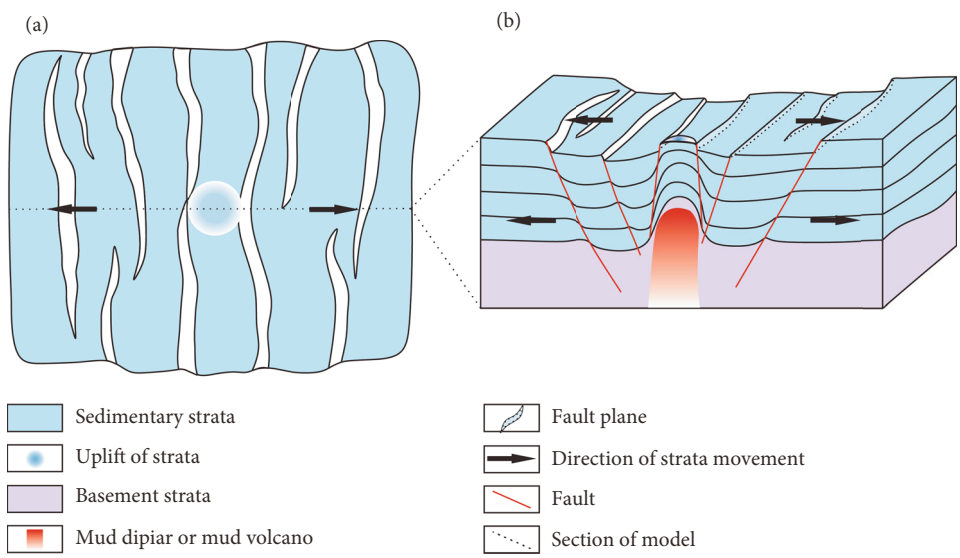

Figure 12: Development mechanism model of mud diapirs/mud volcanoes under extensional background. (a) The top view of the strata after the development of mud diapirs/mud volcanoes in the background of extension. It can be observed that a stratigraphic uplift is on the position where mud diapir or mud volcano develops. There are nearly symmetrical fault zones in the strata on both sides. (b) Three-dimensional map of the development mechanism of mud diapirs/mud volcanoes under the background of extension. The faults developed on both sides of mud diapir/mud volcano are symmetrically distributed and form grabens. In the mud diapir/mud volcano development position, the strata are obviously pulled up, and the top strata are uplifted.

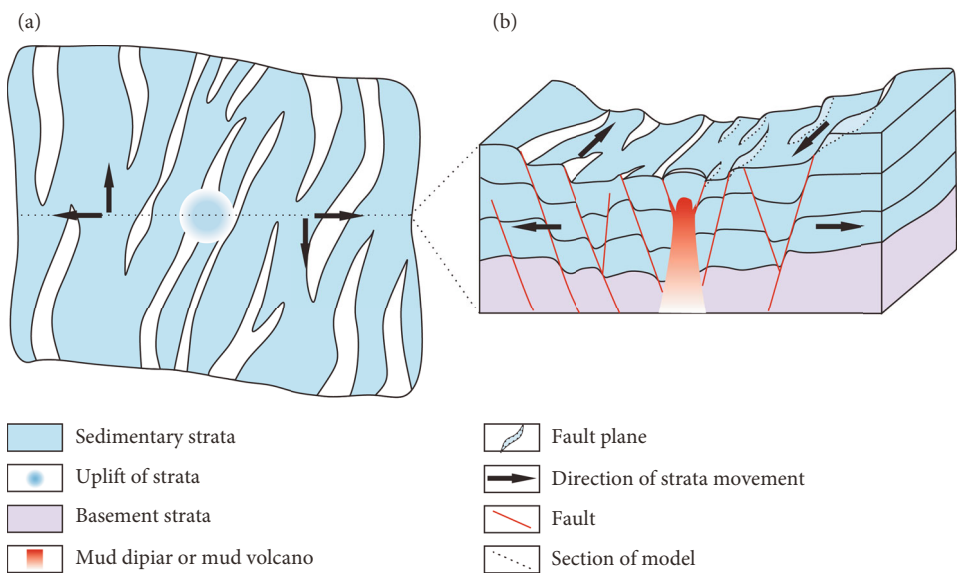

Figure 13: Development mechanism model of mud diapirs/mud volcanoes in the background of transtension. (a) The top view of the strata after the development of mud diapirs/mud volcanoes in the background of transtension. It can be observed that a stratigraphic uplift is on the position where mud diapir or mud volcano develops. There are nearly centrosymmetric fault zones in the strata on both sides. (b) Three-dimensional map of the development mechanism of mud diapirs/mud volcanoes under the background of transtension. The faults on both sides of mud diapir/mud volcano are well developed. Along the faults, muddy fluid intrudes into the fault planes, and the top stratum is uplifted.

the case of relatively single tectonic activity, for example, based on the mainly extensional environment of the Pearl River Mouth Basin and Qiongdongnan Basin, Figure 12 shows that under the condition of only extensional activity, the mud diapir/mud volcano is developed in a columnar shape, and the layers on both sides are symmetrically distributed, forming a graben. In the case of complex tectonic activity background, such as the background of both extension and strike slip in Yinggehai Basin, Figure 13 shows that during the formation of mud diapirs/mud volcanoes, most of the fluid migration is still going upward from the middle directly, but a small part will invade the fault layers along the fault planes and then migrate laterally. On the plane, the fault zones are in echelon distribution, with mud diapir/mud

volcano as the symmetry point, forming a central symmetry distribution.

The development and distribution of fluid-leakage structures in the Zhongjiannan Basin, Yinggehai Basin, Qiongdongnan Basin, and Pearl River Mouth Basin in the northern South China Sea have the following characteristics: there are a large number of mud volcanoes and mud diapirs in the northern part of the Zhongjiannan Basin; there are large mud diapirs in an echelon distribution in the central depression of the Yinggehai Basin; and there are mainly mud diapirs in the Qiongdongnan Basin and Pearl River Mouth Basin, among which the Yinggehai Basin has the largest sizes and the largest number of mud diapirs. Combined with the results from the physical simulation experiments, this paper considers that due to the influence of strike-slip movement in the western part of the South China Sea and the better mud-source material conditions and overpressured environments, fluid-leakage structures are developed in the Zhongjiannan Basin and Yinggehai Basin, with larger sizes and greater quantities. However, due to the difference in sedimentary thickness, the Cenozoic Yinggehai Basin lacks mud volcano structures. The Qiongdongnan Basin and the Pearl River Mouth Basin have the same tensile-stress background, but the Pearl River Mouth Basin still develops more mud diapir structures in the absence of overpressure, which indicates that mud sources and overpressure are not the only factors controlling the development of fluid-leakage structures, and the development of extensional faults can reduce the pressure threshold required for upward fluid migration.

Therefore, the different development of fluid-leakage structures in different Cenozoic basins in the northern South China Sea is due to the differences in the geodynamic, sedimentary, and tectonic settings of these basins. The tensile and strike-slip stress background is conducive to the formation of fluid-seepage structures such as mud diapirs and mud volcanoes. The thinner sedimentary thickness is more conducive to the formation of mud volcanoes. Faults have a certain impact on the formation of mud diapirs and mud volcanoes.

6. Conclusion

(1) In an overpressured environment, if the source of deep muddy fluid is deeper or the overlying sedimentary cap is thicker, the pressure/power required for upward migration of muddy fluid to penetrate the overlying strata is greater

(2) Tectonic activity can promote the development of mud volcanoes/mud diapirs. To a certain extent, tectonic activity can reduce the formation pressure, can effectively reduce the energy required for the formation of mud volcanoes/mud diapirs, and can promote the upwelling of deep fluids

(3) Faults and fractures can be used as channels for the upward migration of deep muddy fluids. On a certain scale, the larger the fault is, the more significant the effect of promoting the development of mud volcanoes/mud diapirs is, and the larger the scale of the mud diapirs/mud volcanoes becomes

(4) According to the results of physical simulation experiments, there are two mechanisms for the development of mud volcanoes/mud diapirs: (i) under the condition of rapid deposition, fine-grained sediments accumulate to form an undercompacted environment, while under the condition of high heat flow, an overpressured environment is formed, resulting in the upwelling of deep fluid material and the formation of mud diapirs or even mud volcanoes; (ii) the fault channel formed by tectonism can reduce the pressure required for the formation of mud diapirs/-mud volcanoes, can provide a channel for the migration of deep mud-source materials, and can lead to the formation of mud diapirs and 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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