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Genetic Mechanism and Evolution of the Covert Fault Zone and Its Oil-Controlling Mode in Qikou Sag, Eastern China

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Abstract: Covert fault zone is an important type of geological phenomenon that is closely related to hydrocarbon formation and distribution but has often been overlooked because it lacks obvious fault displacement and fault plane. To meet this challenge, a novel cognitive framework is proposed in this study, in which criteria for identifying the existence of covert fault zone are developed based on the regional tectonic backgrounds and geophysical data. The Riedel shear model is then utilized to analyze the genetic mechanism of the covert fault zone. The Mohr-Coulomb theory is also introduced to conduct a structural physical simulation to interpret the evolution process of the covert fault zone. Information about the genetic mechanism and evolution of the covert fault zone is finally combined to determine the oil-controlling mode. The study site is Qikou Sag in Eastern China. It is found that the covert fault zone in Qikou Sag meets four recognition criteria and is generated by the stress transferred from the strike-slip activity of the basement fault. Moreover, it can be concluded that the covert fault zone in Qikou Sag contains five evolution stages and controls the reservoir mainly via three aspects, that is, sedimentary sand, subtle traps and oil accumulation mode.

Keywords: covert fault zone; genetic mechanism; Qikou Sag; structure evolution; oil-controlling mode; Riedel shear; Mohr–Coulomb theory

1. Introduction

Fault in sedimentary strata is an important reservoir-controlling factor [1]. Especially for the petroliferous basins in China, the control effects of faults on oil and gas reservoirs is more obvious [2]. Thereby the deeply research of the fault is essential for oil and gas exploration [3–5]. Nowadays, the increase in exploration difficulty makes oil and gas exploration in deep, covert and unconventional fields desirable [6–8]. In particular, the effects of covert tectonic activity on the overlying layers requires further interpretation [9,10]. Moreover, researchers have found some small weak deformation structures in the overlying layers that without obvious fault displacement and fault plane [11,12]. The geological phenomenon formed by these structures are referred to as covert fault zone in this study.

In the past two decades, although few researches taken covert fault zone as an independent geological phenomenon, the small weak deformation structures have shown highly correlations with the distribution of oil and gas [1,10,12–18]. For example, the Ordos Basin in the central parts of China was previously believed to be no fault in the caprocks and its reservoir was controlled by the anticline, lithology and stratigraphic overlap [11]. However, many small weak deformation structures were recently discovered in the overlying layers and these structures control the distribution and migration of hydrocarbon to a great degree [1,9]. Similarly, the string distribution of the reservoirs, sags and domes in the Jinhu and Gaoyou Sag of the Subei Basin, Eastern China is found controlled by the small faults in caprocks [12]. These small faults were caused by the underlying basement faults in North East (NE), North West (NW) and South North (SN) directions [12,19].

Nevertheless, few of the previous studies performed a systematical analysis of the covert fault zone. Its genetic mechanism, evolution and oil-controlling mode are undefined. Fortunately, some referable researches have been presented in the structural geology field. For example, Morley derives a penetrating structure on the basis of the Mohr-Coulomb criterion and Byerlee's legislation [13]. This structure does not have a uniform rupture surface, which is very similar to the covert fault zone. In addition, according to the detailed analysis of the simulation of the strike-slip structure in the plate, Dooly et al. found that there are many small faults (hidden faults) scattered in the en-echelon fault zone under various regional stress in the early stages of fracture development [14]. The deformation difference of these small faults are mainly shown as variance in the maximum principle stress direction, the Riedel (R) shear angle and the construction and evolution modes. Moreover, Hardy studied the overlay deformation (defined as the discrete fault zone) features on the steep basement normal fault in the continuous increasing fault distance by using 2D discrete element modeling and concluded that the activity in the discrete fault zone affects trap formation and fluid migration [17,18].

The aforementioned studies all indicate that although the covert fault zone usually occurs as small faults in linear and discontinuous arrays, its genetic mechanism, evolution and oil-controlling mode can be studied based on the adjacent structures, such as the basement fault, en-echelon distributed small faults, regional stress and so forth. [13,14,17,18]. This was also confirmed by the simulation experiments of Bellahsen [16].

Qikou Sag is the largest hydrocarbon bearing sag of the Bohai Bay Basin in Eastern China [20]. To make clear geological structure of Qikou Sag is crucial for exploring the distribution of oil and gas in the Bohai Bay Basin. In the previous researches, the regional tectonic backgrounds of the Qikou Sag, such as stratigraphic distribution, sedimentary characteristics and basic tectonic characteristics, have been analyzed [21–24]. Many geological structure data are thus summarized. Additionally, some studies on the generation and accumulation of hydrocarbon in the Qikou Sag also have been performed [20,25–30]. These works have accumulated many geophysical data such as seismic profiles and horizontal slices of Qikou Sag. The interpretation of the seismic profiles and horizontal slices can provide the profile and planar characteristics of geological structure patterns, respectively [31–37]. However, scarcely any study has paid attention to the covert fault zone in this sag.

In this paper, to perform a deep analysis of the genetic mechanism, evolution and oil-controlling mode of covert fault zone in Qikou Sag, a novel cognitive framework for the covert fault zone is proposed. In the cognitive framework, the first aim is to establish a set of recognition criteria for identifying the existence of covert fault zone. Then for a covert fault zone, to build a genetic mechanism analysis method on the basis of the R shear model. Additionally, to design a structural physical simulation method based on the Mohr-Coulomb theory for interpreting the evolution process of the covert fault zone. Finally based upon the genetic mechanism and evolution process, to construct the oil-controlling mode of the covert fault zone.

2. Study Area

The Qikou Sag is the largest hydrocarbon bearing sag of the Bohai Bay Basin in Eastern China, located in the center of the Huanghua Depression with an area of about 5280 km^2 [26]. It is divided into land areas on the west side and sea areas on the east side by the Boxi coastline, which is about 250 km long [26]. The sag is controlled by the faults in North NE (NNE), NE and East West (EW) directions and has the characteristics of extensional fault depression. Its strike-slip activity is very active because its basement from the south to the north is passed by the Lanliao strike-slip fault, as shown in

Figure 1 [1,26]. The structural units of Qikou Sag include four negative structural units, namely the Qikou main sag, the Banqiao sub-sag, the Qibei sub-sag and the Qinan sub-sag and four positive structural units named the Beidagang buried hill, the Nandagang buried hill, the along-coastline basement involved fault belt and the Chengbei step-fault belt. The sedimentary caprocks of Qikou Sag have experienced two evolutionary stages: the Paleogene rifting stage and the Neogene depression stage. Seismic and drilling data show that the strata of Qikou Sag are composed of a preceding Paleogene basement and Cenozoic caprocks, which include Shahejie and Dongying formations in Paleogene and Guantao and Minghuazhen formations in Neogene [21].

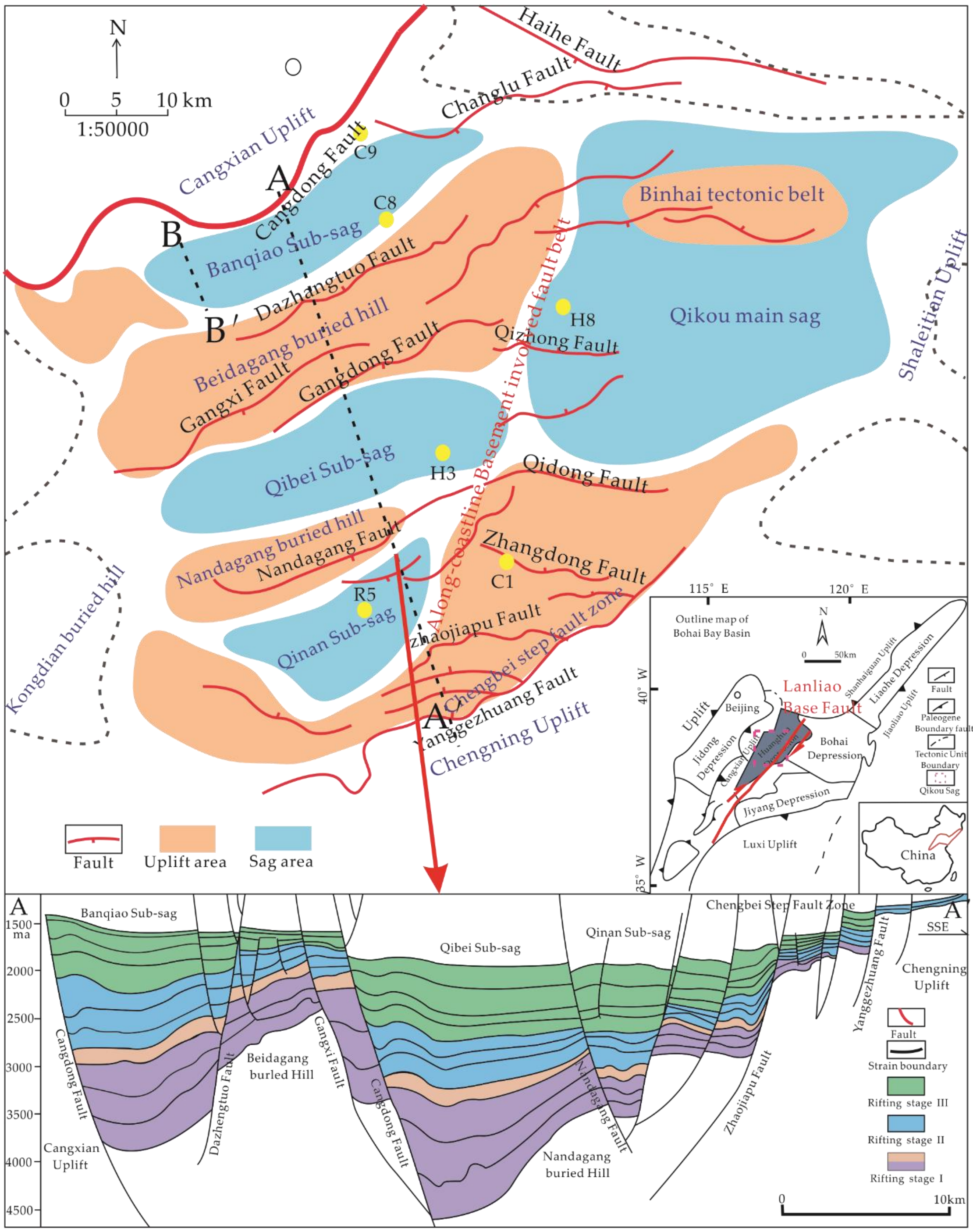

Figure 1. Regional geological map and structural framework of the Qikou Sag, Eastern China (modified from Chen et al., [21]).

3. Methods

In this paper, the genetic mechanism and evolution of the Qikou Sag were analyzed by comprehensive utilization of the regional tectonic backgrounds and geophysical data using the *R* shear model and the Mohr-Coulomb theory. The oil-controlling mode was thereby constructed for the further analysis of reservoir formation. The whole work is named as a novel cognitive framework of covert fault zone. The specific methods of the cognitive framework are introduced in the following subsections.

3.1. Establishment of Recognition Criteria

Following the previous studies, a covert fault zone can be identified by referring to the adjacent structures. The analysis of the adjacent structures in this paper was mainly based on four recognition criteria, that is, single geological element, geophysical data including seismic profiles and horizontal slices of coherent bodies and basement faults.

The single geological element adjacent to the covert fault zone can be determined based on the regional tectonic backgrounds. This is mainly because the features of the adjacent single geological element are always influenced by the covert fault zone. In this paper, the single geological element were classified into nine type, that is, small dominant structures distributed in the en-echelon discontinuous direction, fault structures discretely distributed along a fixed direction, laterally distributed buried hills and depressions, discretely zonal distributed sedimentary facies and sand bodies, discretely directional arranged traps and reservoirs, small faults and small cracks distributed in the dense zone, bead distributed volcanic rock, tectonic abrupt zones and structural separation zones. If one or more types of elements are found in a fault, it can be preliminary regarded as a covert fault zone.

The seismic profiles and horizontal slices of coherent bodies can provide the combined characteristics of the structures [32–37]. Thereby they were also used as recognition criteria in this paper. Based on the preliminary identification, if weak flower-like or semi-flower-like structures were found in the seismic profiles and if small faults or dense fracture zones were found in horizontal slices of coherent bodies, the existence of covert fault zone could be basically determined.

Additionally, basement faults are the fundamental control factors for the development of the covert fault zone in basin cap faults. Consequently, basement faults were used as one of the recognition criteria here. In practice, geophysical data such as the aforementioned seismic profiles and horizontal slices can be used to study whether there are corresponding basement faults under the basin cap. That is to say, mutual validation of these recognition criteria is possible.

On the basis of the four established recognition criteria, identification of the covert fault zone can be achieved, as illustrated in Figure 2.

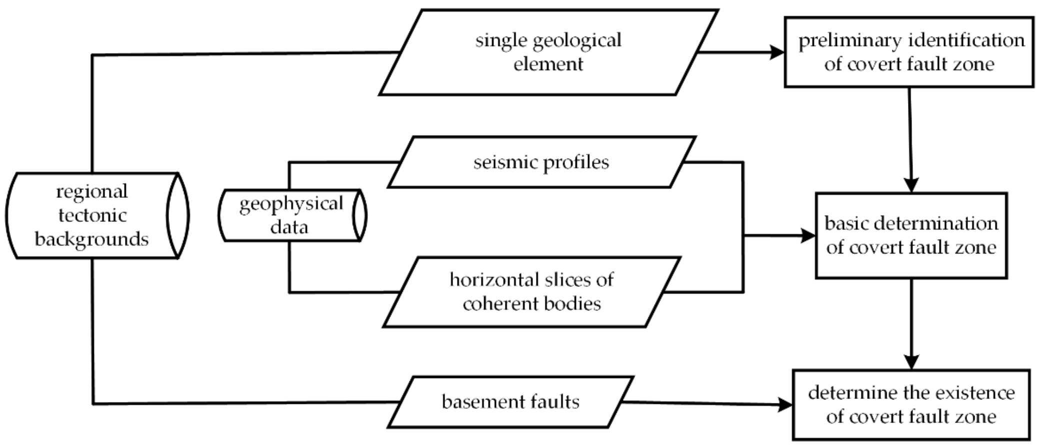

Figure 2. Recognition criteria-based identification method of covert fault zone.

3.2. R Shear Model Based Genetic Mechanism Analysis

The *R* shear model, which is produced by the stress from different tectonic activities, can be used to analyze the genetic mechanism of covert fault zone. This mainly because shear stress is usually expressed as small faults, such as the small dominant structures distributed in the en-echelon discontinuous direction, as discussed in Section 3.1. These small faults are important recognition criteria for identifying of the covert fault zone.

Specifically, influenced by the stress produced by the tectonic activities, such as strike-slip, the shear faults can be classified into five types as shown in Figure 3. As illustrated in Figure 3, *R* shear fault and antithetic *R* shear (R' shear) fault are firstly arisen in sequence. As the displacement increases, the amount of the *R* shear fault increases along the basement fault and low-angle synthetic shear (*P* shear) fault occurs. Then, discontinuous *Y* shear fault parallels to the basement fault begins to appear along with the local tensional (*X* shear) fault that intersects *Y* shear fault at a large angle.

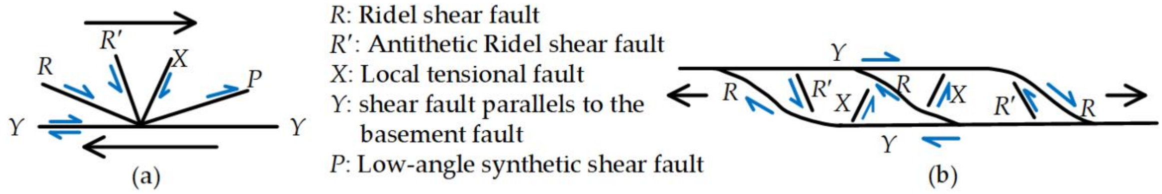

Figure 3. Illustration of the five types of shear fault (*R*, *R'*, *P*, *X*, *Y*): (**a**) Mechanic principle of *R* shear; (**b**) Distribution of shear faults (modified from Dooley et al., [14]).

Accordingly, the genetic mechanism of covert zone are closely related to tectonic activities. Specifically, as shown in Figure 4, actives of different tectonic can generate various stress and thus produce five types of shear faults following the *R* shear model. Then the combination of shear faults forms the geological structures of the covert fault zone [1,32]. The genetic mechanism of a cover fault zone can thereby be analyzed by the interpretation of its geological structures. The flowchart of *R* shear based genetic mechanism analysis is given in Figure 4. The genetic mechanism provides the cognitive basis for the following analysis of evolution.

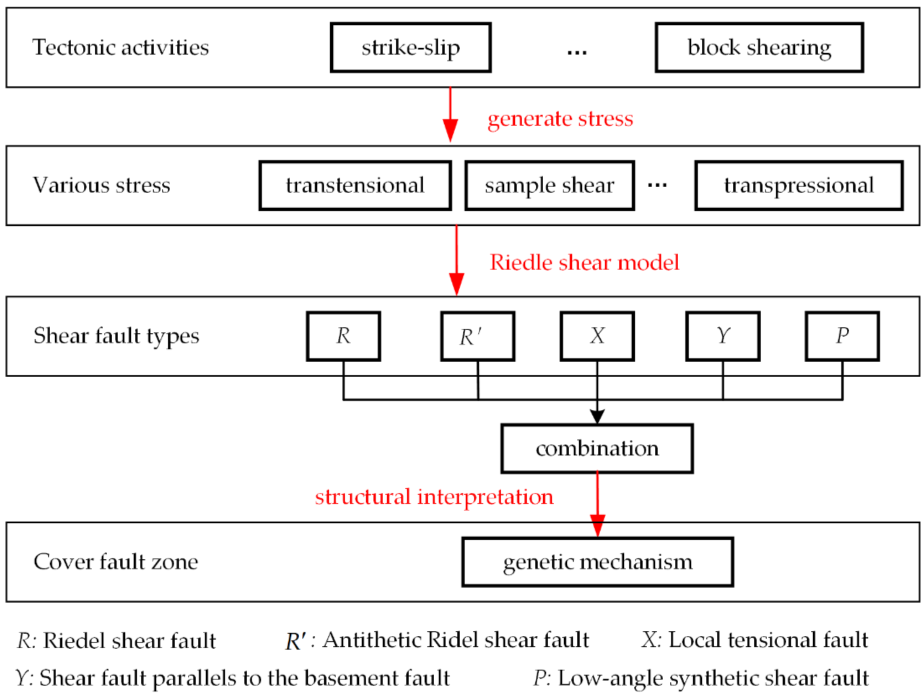

Figure 4. Flowchart of *Riedel* shear based genetic mechanism analysis.

3.3. Mohr-Coulomb Theory Based Evolution Interpretation

Generally, the migration and accumulation of hydrocarbon are accompanied by the evolution of covert fault zone. The shear faults appear in the evolution of covert fault zone can provide reservoir for oil storage, be channels for oil migration or damage those pre-existing oil reservoirs. Therefore, in this paper, a physical simulation method designed based on the Mohr-Coulomb theory is utilized to interpret the evolution of covert fault zone in Qikou Sag.

The Mohr-Coulomb theory is a mathematical model that describes the responses of brittle materials, such as concrete or rubble piles, to shear stress as well as normal stress. In the Mohr-Coulomb theory, Coulomb's friction hypothesis [38] is used to determine the combination of shear and normal stress that will cause fracture of the material. Mohr's circle [39] is used to discover the principal stress that produced the aforementioned combination and find the angle of the plane in which the combination will occurs. Figure 5 displays the diagram of Mohr circle and envelope under triaxial stress. In Figure 5, envelope *a* represents fracture with uniform rupture surface belonging to the dominant stage. Envelope *b* represents the fracture line of the weak zone. Envelope *c* is the initial activity line of basement covert fault, from which the caprocks start to break and the cracks begin to form. The rectangular region between envelopes *a* and *c* represents the weak zone formed by the increasing activity strength of the basement faults. After this period, the fracture and small faults inside the fault zone begin to expand and they begin to be connected with each other to form large-scale fractures, which tend to be dominant [10].

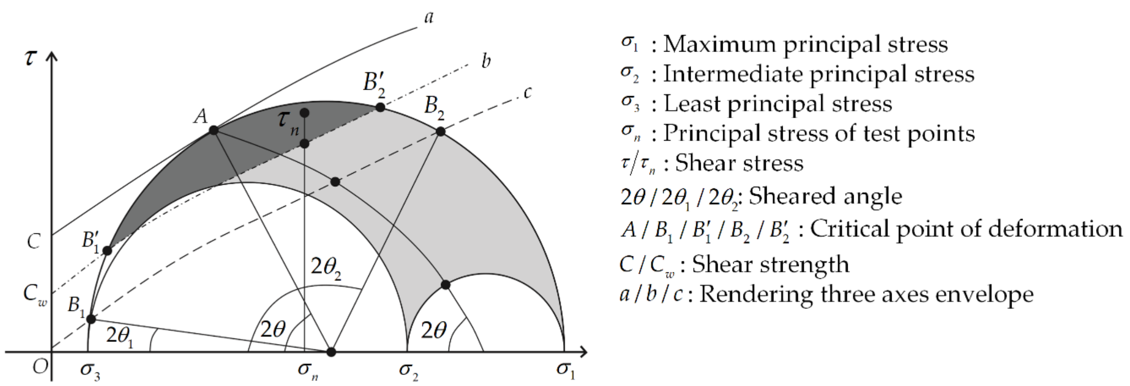

Figure 5. The diagram of the Mohr circle and envelope under triaxial stress (modified from Labuz et al., [40]).

As is shown in Figure 5, the reactivity condition of basement covert fault is the shear stress τ_n along with the strike fault must exceed the shear strength *C*. That is to say, the formation and evolution of the covert fault zone under the stress field generated by the basement fault is essentially a mechanical process. Therefore, the evolution process of the covert fault zone can be interpreted by simulating the mechanical process.

In this study, as shown in Figure 6, the principal stress, shear stress, sheared angle and shear strength were incorporated to design the physical simulation experiment. As displayed in Figure 6a, the size of the experimental device is 46 cm long and 33 cm wide, in which a basement fault with a 45°dip angle is set. Moreover, two active plates are embedded to simulate the motion of faults. As the value of the angle (α) between strip-slip and displacement, which corresponds to the θ shown in Figure 5, has a direct influence on the failure process of rocks, six different angles were designed to interpret the evolution process of the covert fault zone, as shown in Figure 6b.

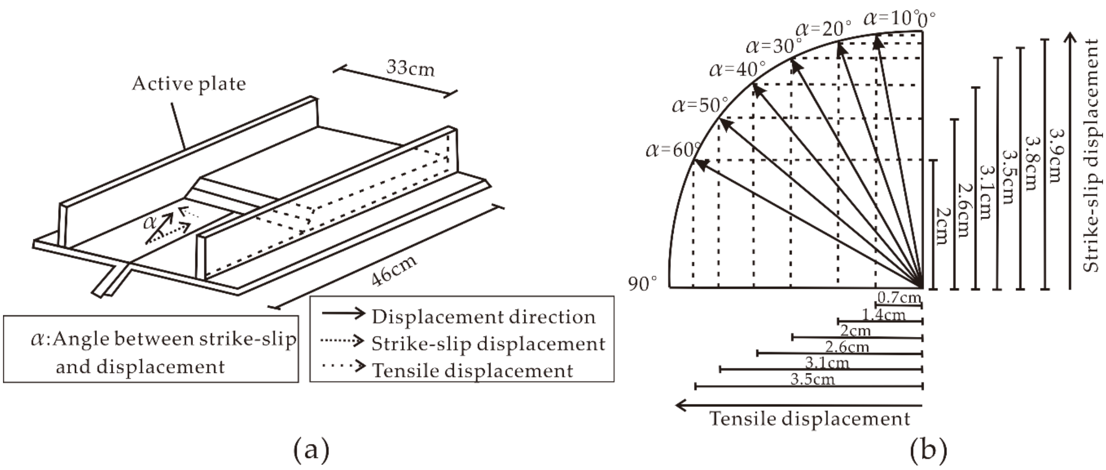

Figure 6. Schematic diagrams of the designed simulation experiment: (**a**) Sketch of the experimental device (modified by Dooley et al., [14]); (**b**) Details of the designed experimental groups.

In the designed physical simulation experiment, over-materials with a thickness of 2 cm were uniformly laid on the top of the model and were manually compacted. In addition, to facilitate the observation of deformation, 2.7 × 2.7 cm grids were printed on the surface of the cover layer in parallel and equispaced as markers during the experiment and the moving wall was pushed and pulled at a constant speed in a certain direction to simulate the right-hand tensioning movement. Moreover, to further study the effect of the covert fault zone on the evolution of oil and gas accumulation, liquid was injected into the cracks during simulation process of the experiment to simply simulate the migration and accumulation of oil. Thereby, the oil-controlling mode of a covert fault zone can be analyzed based upon the genetic mechanism, evolution process and the reservoir forming conditions. During the simulation experiment, the camera was used to take pictures at the same slip of different groups of experiments as shown in Section 4.3.

4. Results and Discussion

4.1. Recognition Criteria of Covert Fault Zone in Qikou Sag

From the comprehensive analysis of the regional tectonic backgrounds and geophysical data in Qikou Sag, four recognition criteria are found inside the sag, namely, the small dominant structures distributed in the en-echelon discontinuous direction (as shown in Figure 7), the linear zone reflected by the slice data, the flower structure reflected by the seismic profiles and the basement faults under the basin cap. Details of these four recognition criteria are given below and they confirm the existence of the covert fault zone in Qikou Sag.

Small dominant structures are found distributed in the en-echelon discontinuous direction. As introduced in Section 3.1, these structures is a type of the single geological element that can be used to preliminary identify the existence of the covert fault zone in the Qikou Sag. As shown in Figure 7, the small dominant structures (faults) on both sides of the covert fault zone have the following characteristics: the fault dip is in the opposite direction and the strike of faults causes mutation. That is, the small dominant structures in the covert fault zone are distributed in the en-echelon discontinuous direction. A series of medium and low amplitude bulges (4–8 km) along the trend of the covert fault zone are also spread out in an echelon pattern.

The linear zone reflected by the slice data is the second criterion found in Qikou Sag. As shown in Figure 8, the coherent slices in Figure 8a show that the deep part, which has a dark band with a low correlation coefficient, has an *s*-shaped strike-slip fault, while the shallow slices in Figure 8b reflect a linear and intermittent distribution of dark bands. These correspondences between the deep and shallow slices indicate the high possibility of the existence of a covert fault zone.

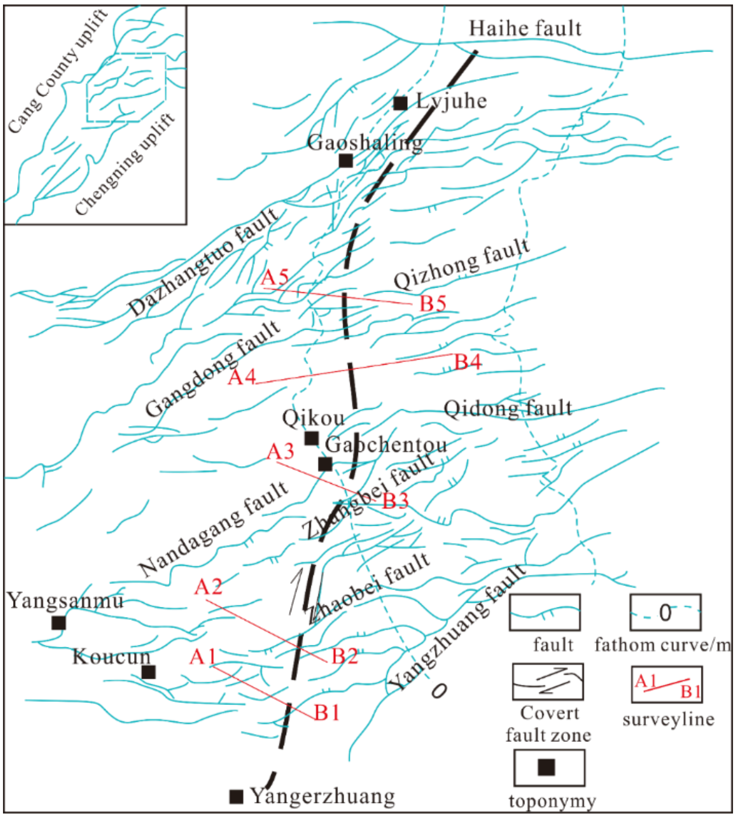

Figure 7. Distribution of small dominant Fault and tectonic location in Qikou Sag (modified from Qi et al., [28]).

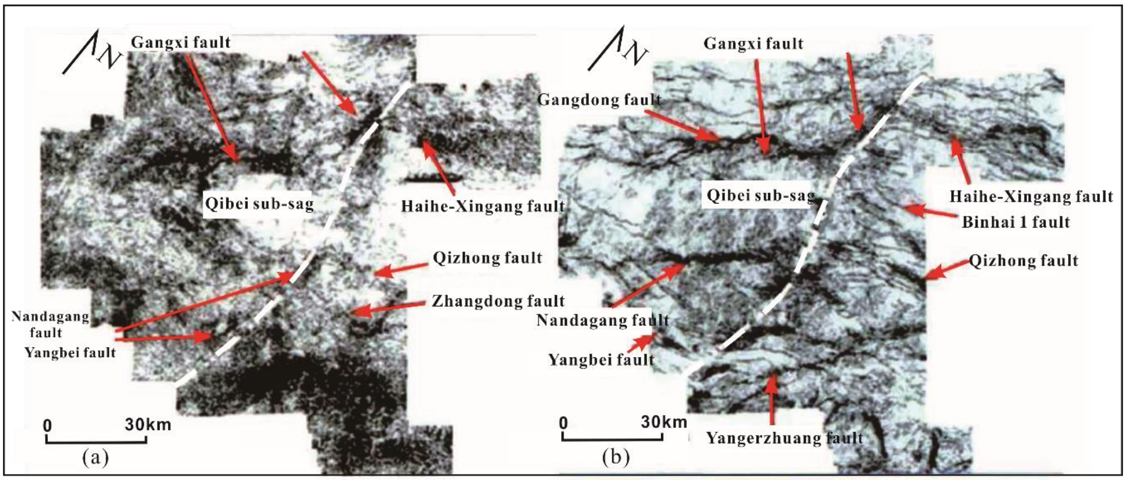

Figure 8. Coherent slices of the covert fault zone in Qikou Sag: (**a**) 3320 ms slices of the coherence cube; (**b**) 1320 ms slices of the coherence cube (modified from Zhou et al., [1]).

The flower structure reflected by the seismic profiles is the third criterion of covert fault zone in Qikou Sag. Figure 9a–d show the five profiles, that is, the profile A1–B1, the profile A2–B2, the profile A3–B3, the profile A4–B4 and the profile A5–B5 whose positions are provided in Figure 7. In the Southern section, as is shown in Figure 9a–c, the typical negative flower-like structure develops in the basement in the Paleogene era. Moreover, the flower-like structure gradually converges into a steep downward fault in the deep part. In the middle section, as shown in Figure 9d, the deep trunk strike-slip fault with an overall steep locally curved and irregular section is inserted into the base. Moreover, the deep trunk strike-slip fault is generally spread upward in a flower shape which is a normal fault on the upside and a reverse fault downwards. The covert fault zone formed in the Paleogene era and is characterized by a relatively wide and gentle flower structure. For the Northern section, the deformation of the Paleogene formation is generally confined to the regional bottom slip interface as illustrated in Figure 9e. The upper plate of the main slip zone shows folded deformation, while the tectonic features of the late Mesozoic are maintained below, with almost no deformation.

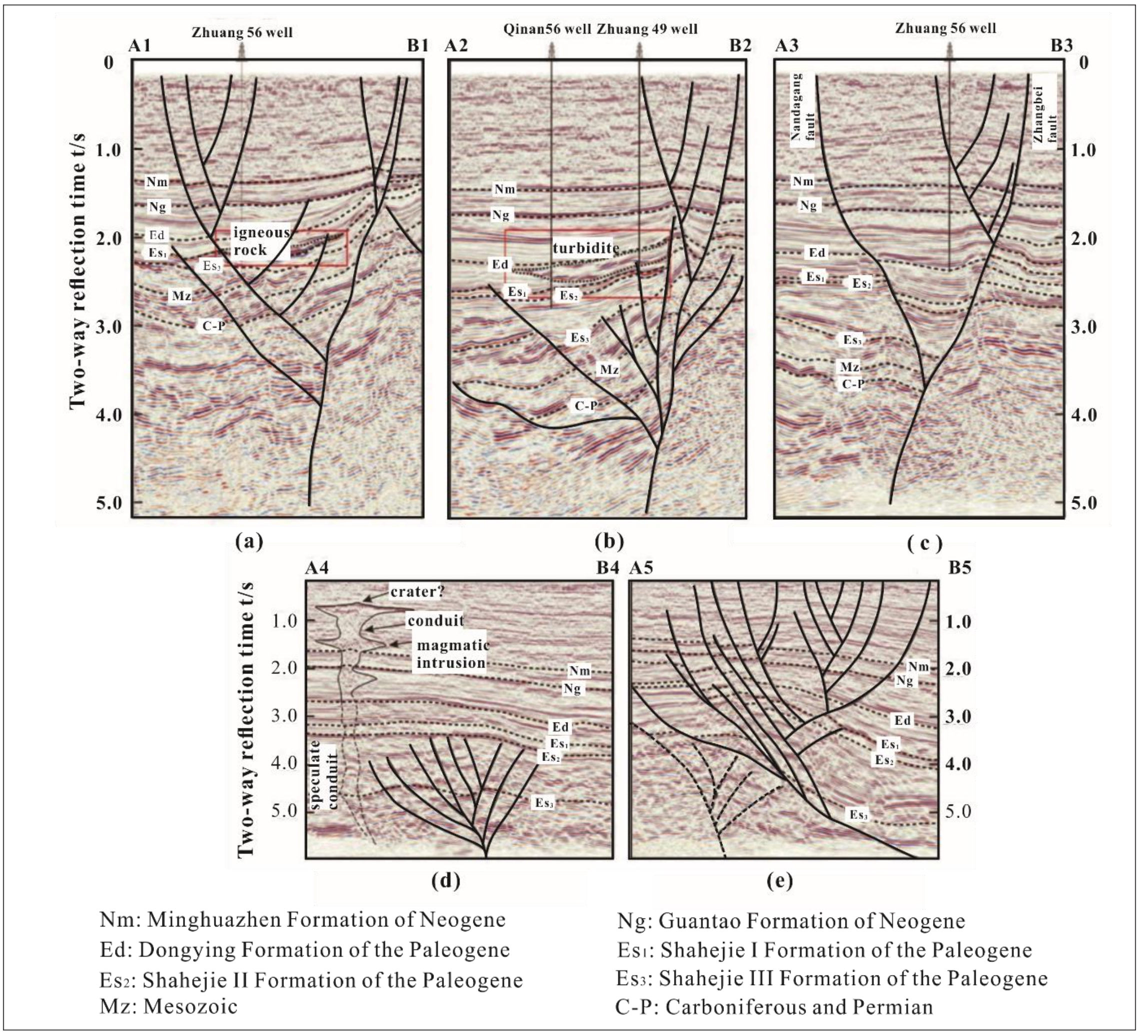

Figure 9. Profile characteristics of covert fault zone in Qikou Sag: (**a**) Profile A1–B1 of the Southern section; (**b**) Profile A2–B2 of the Southern section; (**c**) Profile A3–B3 of the Southern section; (**d**) Profile A4–B4 of the middle section; (**e**) Profile A5–B5 of the Northern section (modified from Qi et al., [28]).

Basement faults under the basin cap is the fourth criterion of the covert fault zone in Qikou Sag. The crystalline basement structure of Qikou Sag is presented in Figure 10. The covert fault zone of Qikou Sag shows completely different characteristics in terms of the aeromagnetic anomalies on both sides: the Luxi basement on the left presents a highly abnormal area with complex changes and the geological block has an overall NE strike. It can be concluded that the Taihang mountain basement on the right is characterized by an open positive and negative alternation of NNE and NE. Further, the area below the Qikou Sag is shown as the "triple point" part of the three crystalline basements of Luxi, Taihang and Yanshan. This special structural position is just like the weak zone described by Morley [10], which is prone to wiggle under the regional stress field and the covert fault zone can be easily formed by long-term weak activity or local lithologic unevenness. The buried hills and depressions on both sides of the covert fault zone are distributed in hidden places.

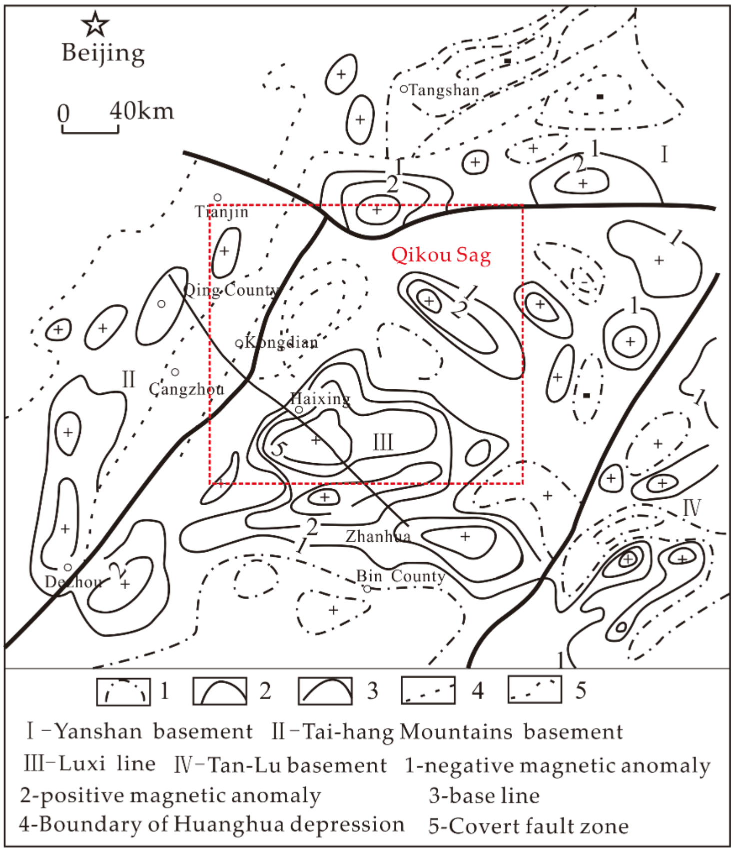

Figure 10. Crystalline basement plot of the Huanghua depression which contains the Qikou Sag.

4.2. Genetic Mechanism of the Covert Fault Zone in Qikou Sag

Through a comprehensive analysis of the tectonic activities of Qikou Sag and the four recognition criteria described in Section 4.1, it can be concluded that in the Cenozoic era, the Pacific plate subducted from NW to East West (EW), causing the Eastern part of the Chinese mainland to be under the stress field of right-handed tension. Therefore, the NNE deep basement fault near the coastline of Qikou depression has strong dextral strike-slip under this background, which is the basis for the formation of the Cenozoic structural diversity of the coastal zone. Based on the *R* shear model, *R* shear and its conjugate, *R*' shear, formed first and *P* shear formed later, according to the sequence of brittle strike-slip fracture formation. In addition, the Luxi basement and Taihang mountain basement are in contact with Qikou Sag and the splicing zone is shown as a weak zone, which is most prone to form shear fracture, as shown in Figure 11.

Overall, in the south section of the covert fault zone, the basement uplift is large and the buried depth of the basement strike-slip fault has a significant influence on the overburden deformation. The middle section is the rhombic region between the Qidong fault and the Gangdong fault. The root of the deep main strike-slip fault in this rhombic region is inserted into the basement, forming a flower-like structure and the strike of faults on both sides of the fault zone changes significantly. In the Northern section, the dense fault zone enters the slip zone, resulting in the upper displacement of the fault being adjusted so that it disappears. In general, the covert fault zone in Qikou Sag formed under the control of the strike-slip activity of the basement.

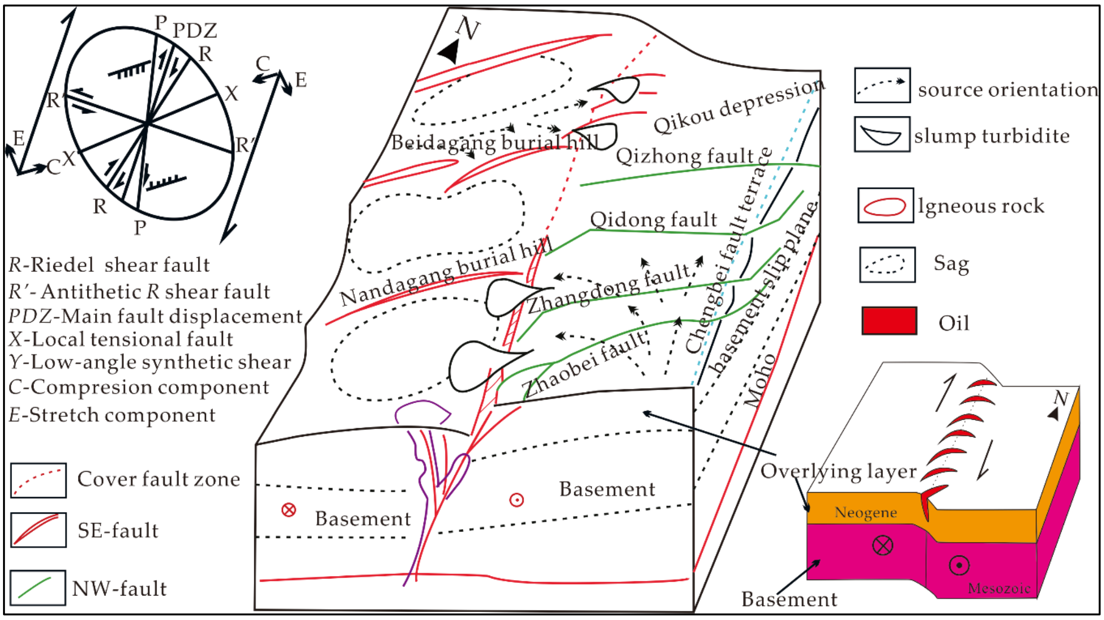

Figure 11. Genetic mechanism mode of the covert fault zone in Qikou Sag.

4.3. Evolutionary Characteristic of the Covert Fault Zone in Qikou Sag

The simulated evolution processes of the covert fault zone are presented in Figure 12. As shown in Figure 12, when the torsional angle α is 10° or 20°, the caprock tectonic deformation style is characterized by a series of relatively flat cracks arranged in an echelon. Meanwhile, the angle between the direction of crack and fault zone is about 35°, which is similar to the early and middle construction styles of simple shear. When the angle α is 30–50°, *R* shear faults still are arranged in an echelon but the plane morphology of most fractures will no longer be straight. Additionally, the angle between *R* shear faults and the direction of the fault changes from 30–40° to 5–10°, showing an arc or "*S*" shape. When angle α increases to 60 °, the angle between *R* shear faults and the direction of the fault reduces significantly to about 13° and the echelon feature of the fracture zone is no longer obvious.

To further investigate the evolution process of the covert fault zone, physical simulation experiments were performed under two stress conditions: transtensional stress and transpressional stress. The evolution processes are presented in Figure 13. As shown in Figure 13, the basement, stress and strain are the three conditions that control the formation and evolution of covert faults. Under the condition of increasing activity strength of basement faults, the caprock fault experiences a multi-stage change from "covert" to "dominant."

The first stage of the covert fault zone evolution is the induced breakage stage as shown in Figure 13. In this stage, the EW rupture is small-scale, scattered and isolated, with no break distance and poor regularity. In the covert fault zone, the induced fracture zone is roughly parallel to the strike direction and presents a dendritic shape. There is no main slip surface in the induced fractures. The second stage of the covert fault zone evolution is the localized fault stage. Under the continuous action of external stress, the activity of the basement fracture intensifies. Most *R* shears change into small faults with fault displacement. Due to the increases in the sizes of the above *R* shears, small localized rupture surfaces develop in the covert fault zone. However, they still fail to cut through covers. In this stage, *P* shears start to appear. This stage occurs under the condition of transtensional stress, while it does not occur under transpressional stress, as shown in Figure 13. The third stage of the covert fault zone evolution is the major fault stage. As the strike-slip effect of basement fault is further intensified, the writhing and tearing effect of cap layer is strengthened. As the en-echelon *R* shear increases, short *P* shear faults gradually appear, which are limited to the area between en-echelon faults. The *P* shear faults may occur at intervals or continuously develop to form local dominant faults. The fourth stage of the covert fault zone evolution is the major slip stage. As shown in Figure 13, the discontinuous partial main faults of the last stage interconnect with each other and develop into larger *Y* faults. Early-formed en-echelon *R* faults are cut into branch faults on both sides of the main faults. The last stage of the covert fault zone evolution is the slide and breakage stage. All *Y* shear faults merge with basement strike-slip faults and are shown as typical negative flower structures in the profile. In addition, many small branch faults develop along both sides of the main faults, and, combined with main faults, form a plumose structure. In this stage, the en-echelon fault are fully connected and destroyed to form the main fault plane.

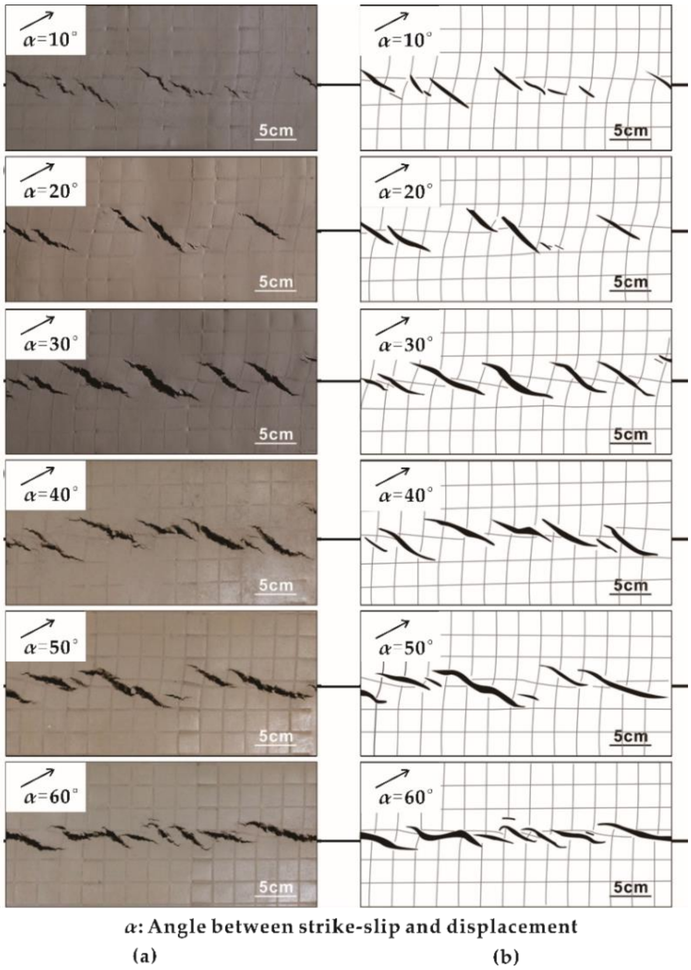

Figure 12. The evolution processes of the covert fault zone: (**a**) Experimental photos of different α angles; (**b**) Sketches of the photos in (**a**).

Based on the aforementioned analysis and oil filling simulation, the oil accumulation degree in different evolution stages is shown in Table 1. As shown, in the induced breakage stage, the structural deformation of the covert fault zone is in the form of a weak echelon, in which 20% of the trap area is filled and only small amounts of oil and gas accumulate in the fault traps close to the oil source. In the localized fault stage, small fractures expand to form larger fractures with an en-echelon distribution and small fractures began to appear at the edge of the *R* shear. In the covert fault zone, as a whole, oil and gas show an en-echelon fault block aggregation pattern and 50% of the trap area is filled. In the major fault stage, secondary *P* shear cracks begin to appear and the trap filling degree reaches 75%. In the major slip stage and slide and breakage stage, the covert fault zone is penetrated by *Y* shear and the fault properties of the covert fault zone are very obvious. The whole fault zone is rich in oil and gas and the trap is as full as 90%.

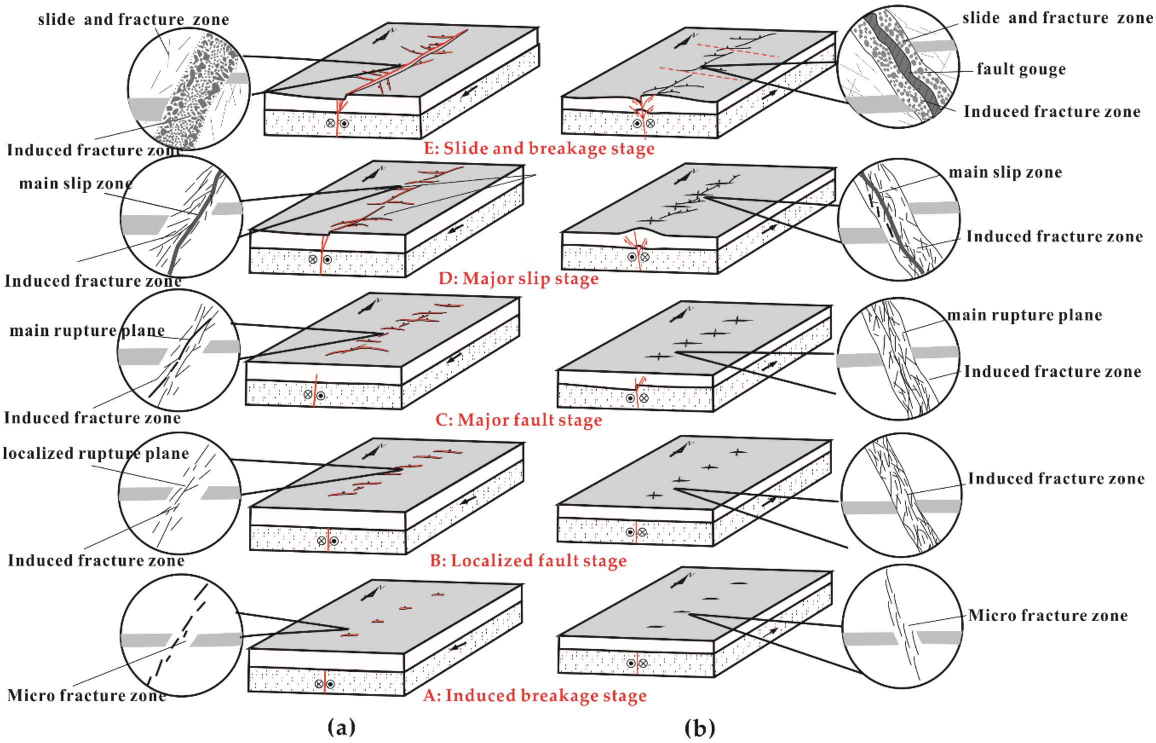

Figure 13. The evolution processes of the covert fault zone in Qikou Sag: (**a**) Under transtensional stress; (**b**) Under transpressional stress.

Table 1. Oil accumulation degree in different evolution stages.

Stage	Time Sequence	Deformation Strength (cm)	Oil Filling Level (mL)	Cumulative Time (min)	Trap Filled Area (%)
A	Early	1.56	12	3	20
B	Early-to-mid	3.76	20	7	55
C	Middle	7.32	24	9	75
D/E	End	11.6	24	10	90

4.4. Oil-Controlling Mode of the Covert Fault Zone in Qikou Sag

The genetic mechanism (as described in Section 4.2) and evolution process (as described in Section 4.3) of the covert fault zone control the thermal evolution and distribution of the source rock, reservoir physical properties, trap development and transport conditions and thus affect the law of hydrocarbon accumulation distribution [41]. Considering the geological conditions of the Qikou Sag, the distribution of the sedimentary sand, the formation and distribution of subtle traps and the oil accumulation mode are utilized to analyze the oil-controlling mode of the covert fault zone in Qikou Sag.

The controlling effect of sedimentary sand is mainly expressed as the cutting and joining action on sedimentary sand. The covert fault zone controls the formation and distribution of a large number of echelon and discontinuous small fault zones, which form the combined relationship between cutting and connection. As shown in Figure 14, the small structures shown in profile, such as fault terraces and graben, form fracture zones and the river channel can easily use its strike to wash down and cut and form sediment unloading zones along the covert fault zone. The covert fault zone of Qikou Sag has an obvious controlling effect on sedimentary facies, among which the basement fault in the Southern section is strong. The dominant fault in Zhangbei is formed in the caprock and the covert fault zone is spread in the left echelon pattern to the north. The fan delta of the Shasan Segment extends into the lake basin [42,43] and the source water system carries a large number of sand bodies deposited along the covert fault zone in the echelon pattern.

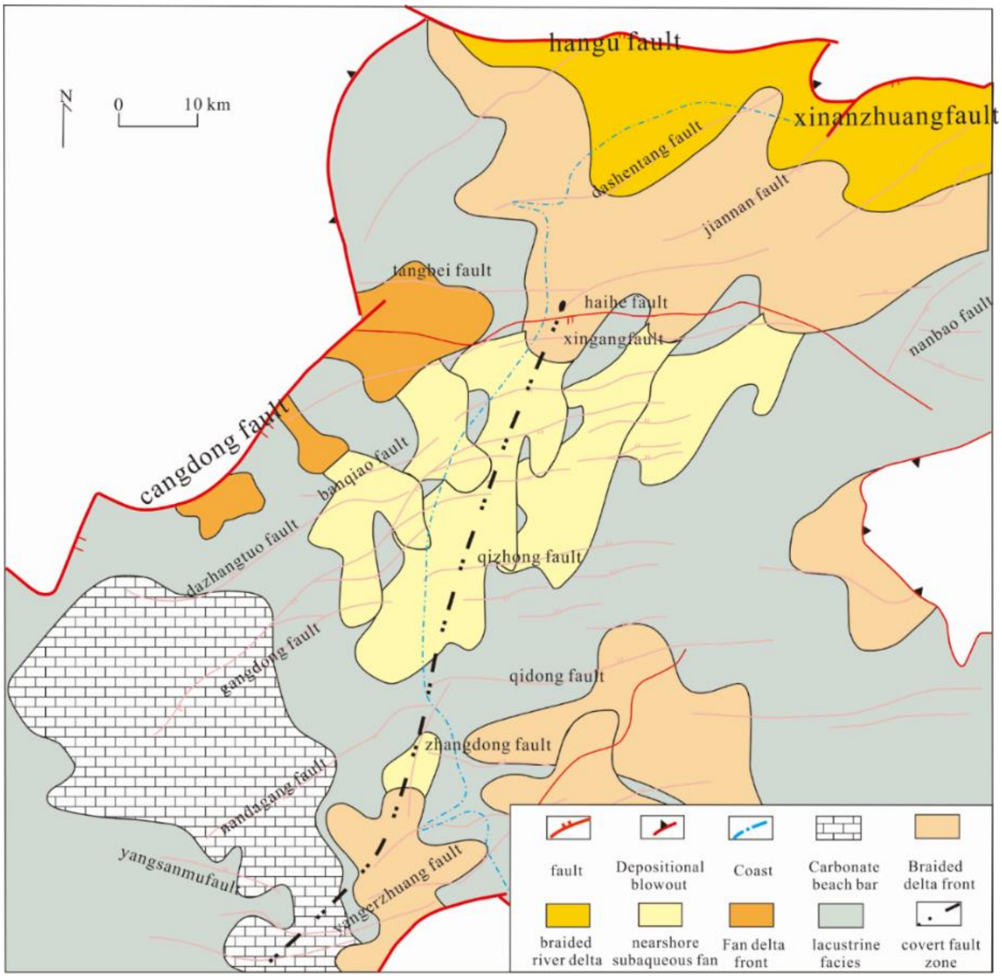

Figure 14. Controlling effect of sedimentary reservoirs.

There are primarily four kinds of subtle trap in the covert fault zone in Qikou Sag. One kind is NNE minor faults which are a kind of intersecting occlusion formed by basement fault activity in the cover. The second type is the combination of NE and NNE covert faults, which produce the arc-shaped covert fault block traps. Note that although these two traps have a tectonic background controlled by the covert fault zone, the genesis of traps is controlled by both lithology and structure. The third kind is the microstructure traps formed under the condition of different compactions of sandstone or low strength tectonic activity. The trap range of it is low, while its oil–bearing height is generally small. The fourth subtle trap includes lithologic updip pinchout traps controlled by low-amplitude slope break zones and the faults in both directions have not been developed. It is, in fact, a kind of subtle trap formed by the reconstruction of paleogeomorphology of covert fault zone.

The oil accumulation mode is the third aspect controlled by the covert fault zone in Qikou Sag. There are primarily four kinds of oil accumulation mode in the covert fault zone of Qikou Sag. As shown in Figure 15a, in the early stages of evolution under the condition of weak deformation, there are only a small number of faults, which form a few small fault block traps and they appear to be intermittent echelon or isolated and dispersed. The strike is inconsecutive and the connectivity of vertical channels is poor. In the early-to-mid stage of the evolution, as shown in Figure 15b, it can be concluded that under the conditions of medium and strong deformation, the number of faults in the covert fault zone is relatively small and the faults show an echelon arrangement. A series of small snout and fault block traps constitute the trap belt, with no connection in the strike and good connectivity in the vertical channel. In the middle stage of the evolution, as shown in Figure 15c, under the condition of medium and strong deformation, the dense development of small faults or small cracks shows an intermittent zonal distribution, forming a large number of larger fault blocks to form the trap belt. The migration channels are connected intermittently in the strike and the vertical channel connectivity is good. At the end stage of the evolution, as is shown in Figure 15d, the deformation intensity of faults is large, the small faults are densely distributed in zones and the main fault surface is almost complete. The fault block group is formed on the covert fault zone and the three-dimensional migration channel is formed in the covert fault zone. In this mode, the blank sections near the beaded oil reservoirs and the grid intersection of the covert fault zone are the potential regions and target areas.

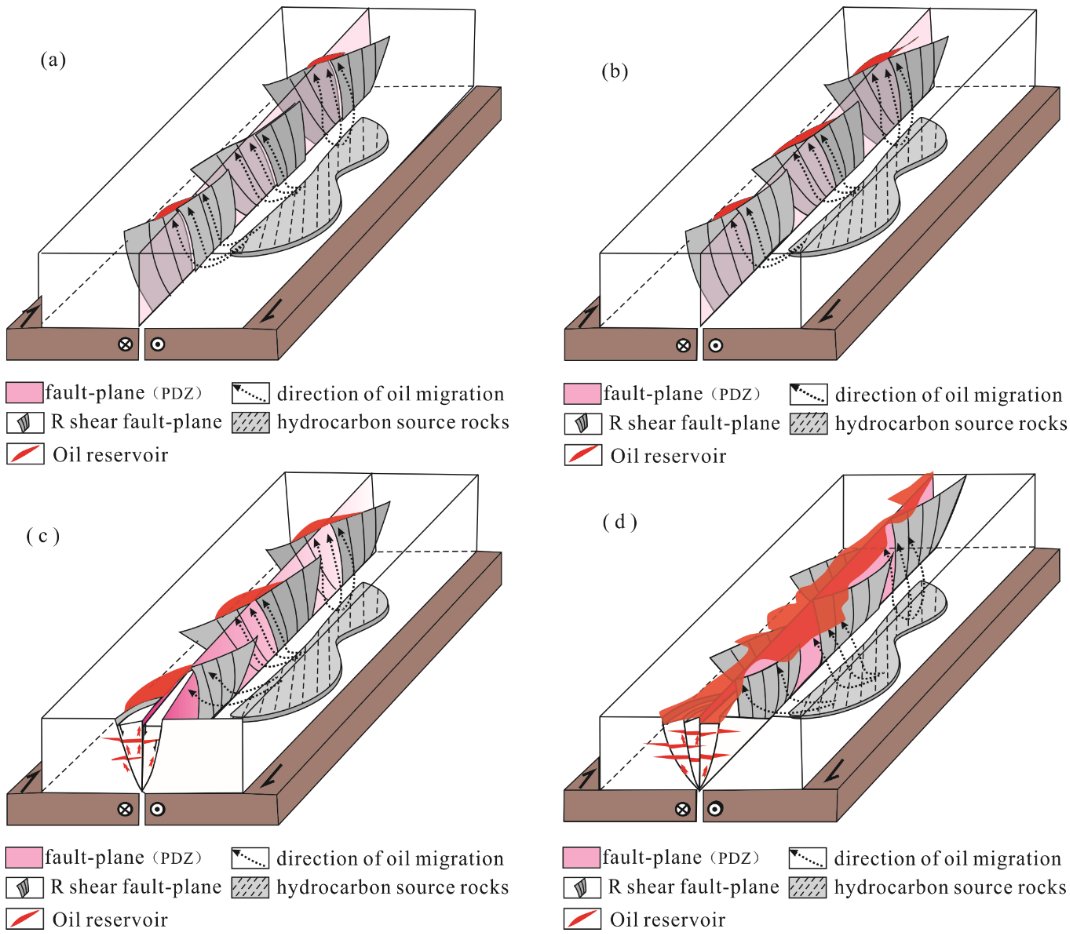

Figure 15. Oil accumulation model of the covert fault zone: (**a**) Early stage; (**b**) Early-to-mid stage; (**c**) Middle stage; (**d**) End stage.

According to the aforementioned controlling effects of the distribution of the sedimentary sand, the formation and distribution of subtle traps and the oil accumulation mode in the south, middle and north segments of the covert fault zone in Qikou Sag, three types of oil-controlling mode are established, as shown in Figure 16.

For the three-layer type shown in Figure 16a, the roots and branches of the floral structure can be used as an oil source fault with good trap, transmission and dynamic conditions. In deep series of strata, the bedrock buried hill reservoirs, fractured reservoirs and unconformity reservoirs form. The faulted noses and fault block reservoirs that formed in the Paleogene era and Neogene era have an en-echelon fault block oil trap accumulation mode. The complex oil and gas accumulation zone can be called a sandwich type vertical distribution mode. While for the mezzanine gathered type shown in Figure 16b, weak strike-slip activity of basement faults connects the oil source faults formed in the Neogene era. The Neogene caprock has relatively good sealing conditions and the oil and gas accumulate in the formations from the Paleogene era. The pattern can also be called a pie vertical distribution mode. By contrast, for the cover layer type shown in Figure 16c, basement faulting leads to the good source rock conditions and reservoir conditions. With good transmissibility in the vertical direction, oil and gas are mainly concentrated in formations from the Neogene era, which can also be called a pizza type vertical distribution mode.

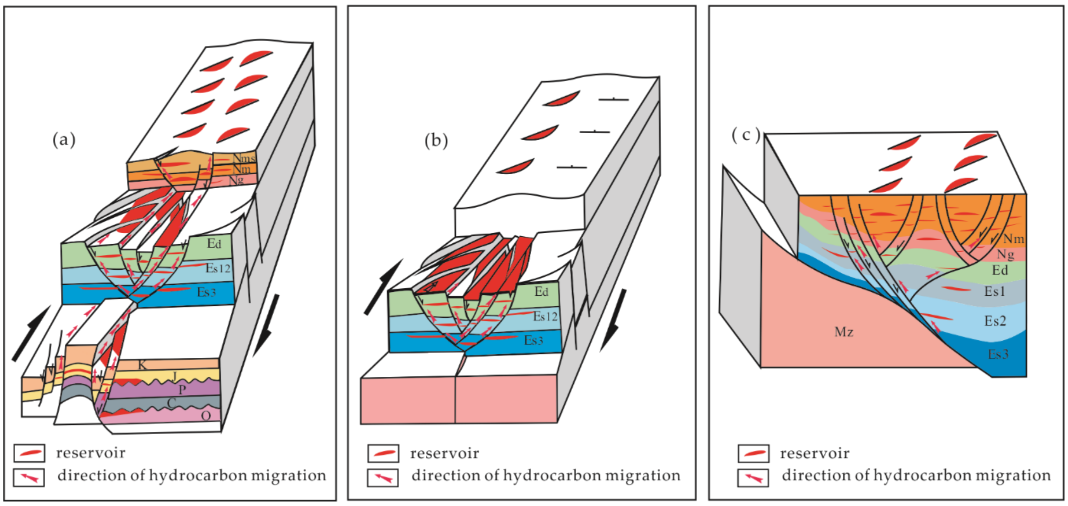

Figure 16. Oil-controlling mode of the covert fault zone in Qikou Sag: (**a**) Three-layer type; (**b**) Mezzanine gathered type; (**c**) Caprock type.

5. Conclusions

A novel cognitive framework of the covert fault zone is proposed in this paper. In the framework, a method for the establishment of recognition criteria is firstly presented for the identification of the covert fault zone. In this method, both the regional tectonic backgrounds and geophysical data of the adjacent structures are considered for the identification of the covert fault zone. Accordingly, the genetic mechanism of the covert fault zone is analyzed based on combination patterns of shear faults generated by the stress transferred from the activities of the basement fault following the *R* shear model. For the evolution interpretation of the covert fault zone, a structural physical simulation method is designed based on the Mohr-Coulomb theory. On the basis of the information about the genetic mechanism and evolution of the covert fault zone and the reservoir forming condition in the study site, the oil-controlling mode of the covert fault zone is investigated.

Studies on the Qikou Sag located in Eastern China have shown that it has four main recognition criteria, that is, en-echelon distributed small dominant structures, horizontal slices of coherent bodies, seismic profile and basement faults. Moreover, it is found that the covert fault zone in Qikou Sag is generated by the stress transferred from the strike-slip activity of the basement fault. Besides, the evolutionary characteristics show that the evolution process of the covert fault zone in Qikou Sag contains five stages: the induced breakage stage, the localized fault stage, the major fault stage, the major slip stage and the slide and breakage stage. In addition, it is concluded that the oil-controlling mode of the covert fault zone in Qikou Sag includes three types, namely the three-layer type, the mezzanine gathered type and the caprock type. Overall, the proposed cognitive framework can also be expanded to other study areas based on the corresponding regional tectonic background and geophysical data. For further improvement of the cognitive framework, variation in stress will be considered in future studies.

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