Development characteristics and formation mechanism of two-phase transfer zone during rifting in Wushi Sag, Beibuwan Basin, South China Sea

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Abstract. Based on the three-dimensional seismic dataset, we consider a key area in Beibuwan Basin, South China Sea, combined with quantitative analysis method, in order to define the features of transfer zone, and its temporal spatial development mechanism is revealed. The two boundary faults in the study area constitute an S-type fault system which does not connect. During the Paleogene rifting, the fault systems and Structuralstratigraphic characteristics between Eocene and Oligocene rifting sequences are different, the ways and quantities of transfer displacement are also distinctly different: (1) The two-phase of Eocene and Oligocene generally developed transfer zones, which were controlled by the structure background and boundary conditions, the formation mechanism of the transfer zone was different in time and space, the distribution of the transfer zone was distinctly different; (2) The Ailaoshan-Honghe strike slip fault, the extension derived from the expansion of the South China Sea have a significant impact on the transfer zone formation and characteristics. The segmented growth of the fault has a direct impact on the formation of the transfer zone. This study reveals the formation mechanism of the transfer zone of superimposed basins in China offshore, which is beneficial to hydrocarbon accumulation in Eocene and Oligocene sequences.

1. Introduction
In rift systems, transfer zones are usually able to transfer displacement and deformation from one fault to another in two forms[1]: "hard connection" [2] or "soft connection" [3]. Beibuwan Basin is located in the South China Sea(figure 1a). As an important petroliferous sag in Beibuwan Basin, Wushi sag(WSG) is East-West trending(figure 1b). We focus on the area of WSG, Paleogene rift stage, Eocene and Oligocene sequence. Affected by regional left lateral strike slip and horizontal tension, the geometric characteristics and displacement form of faults in the study area have changed significantly. From bottom to top, the Paleogene Changliu formation, Liushagang formation, Weizhou formation, Neogene Xiayang formation, Jiaowei formation and Dengloujiao formation were successively deposited(figure 1c). The fault characteristics and structural styles of different tectonic stages in the depression have been studied by predecessors, but there are still several important problems. What is the temporal and spatial formation mechanism of the transfer zone in the rifting stages? The structural style and distribution of the transfer zone and its relationship with hydrocarbon accumulation still need further study.
2. Materials and Methods

2.1. Quantitative identification of transfer zone

On the basis of seismic data, fault activity velocity, fault distance depth curve and fault displacement distance curve are used to quantitatively identify the transfer zone.

2.1.1. Quantitative identification method of transfer zone. Fault activity velocity: the ratio of the difference between the thickness of the upper and lower walls of the fault and the sedimentary geological age of the fault. The low value area of the curve indicates that the fault activity is weak, and it is the connecting part of the fault segment growth, that is, the development part of the transfer zone. Fault distance depth curve: select the vertical fault distance development value of each layer on the seismic section to draw the curve. When the fault is developed, the fault in the isolated growth stage has the characteristics of small shallow and deep fault distance on the section, and the peak value appears in the middle layer. The low value area of the curve is the development location of the transfer zone. Fault displacement distance curve: the values of fault displacement and fault distance on the seismic section are read equidistant, which are taken as the horizontal and vertical coordinates of the curve and plotted. Similar to the activity velocity curve, the low value point of the curve is the development position of the transfer zone[4]. This method is a common method for identifying the transfer zone.

2.1.2. Quantitative identification process of transfer zone. Seismic sections are selected equidistantly to quantitatively determine the typical faults in the study area, and then determine the development period and horizon of the transfer zone. Fault 7 developed earlier, the fault activity velocity at the positions of line 850 and line 1750 show low value points, and the same line position on the displacement fault distance curve (figure 2a, b) is also a low value area. The fault distance depth curve (figure 3a) shows that there are low value areas in Weizhou formation and Liushagang formation; the activity velocity of fault 6 is generally high The vertical fault distance curve (figure 3a) shows that low value points appear in the deposition period of Weizhou formation and Liushagang formation.
Figure 2. Fault activity velocity and Fault displacement distance curve (the left side of each curve is the fault displacement curve, and the right side is the fault activity velocity). (a) Fault 7. (b) Fault 6. (c) Fault ws175. (d) Fault ws221. (e) Fault ws230. (f) Fault ws227. (g) Fault ws161. (h) Fault ws235. (i) Fault ws229.

The fault ws230, fault ws161 and fault ws235, which began to develop under the strong tension environment, have strong activity in Weizhou formation, with low value points (figure 2 e, g, h) at 3110 and 1700 survey line, respectively, indicating that the fault grows in segments, that is, a transfer zone is developed; on the distance depth curve (figure 3 e, b, c), there is a low value point of fault ws161 and fault ws235 in Weizhou formation.

In strike slip-extensional environment, low value points appear in line 750, line 950, line 2600 and line 1750 of ws221, ws227 and ws229 faults with strong activity (figure 2d, f, i), indicating that transfer zones are developed in the middle and tail segments of the above faults; while the Fault distance depth curve (figure 3d, b, c) show that the horizons of transfer zones are different, there is a low value area in the third member of Weizhou formation of ws221 fault, a low value area in the first member of ws227 fault flow, and a low value area in the second member of Weizhou formation of ws229 fault.

Figure 3. Fault distance depth curve. (a) Fault 7 (red), Fault 6 (blue). (b) Fault ws227 (red), Fault ws161 (blue). (c) Fault ws235 (red), Fault ws229 (blue). (d) Fault ws221 (red), Fault ws175 (blue). (e) Fault ws230 (red).

Based on the above quantitative analysis, the common understanding of the eastern area of WSG is...
as follows: a. collateral transfer zone: fault ws229, fault ws161 and fault ws161; b. overlapping transfer zone: fault 6 and 7 fault, fault ws227, fault ws179 and fault ws176; c. approaching transfer zone: fault ws175; d. collinear transfer zone: fault ws167 and fault ws235; e. turning transfer zone: fault ws221.

2.2. Types and characteristics of transfer zones

2.2.1. collateral transfer zone. It is composed of two or more opposite collateral faults. The displacement and deformation between faults are regulated by connecting faults or oblique bulges, and the displacement between main faults increases and decreases along the strike. The major faults are parallel in nearly east-west direction, and the connecting faults are developed on one side of the descending wall of ws230 fault, forming a "hard connection"(figure 4c). On the seismic profile (figure 4c), the wave group of the reflection layer between the fault ws230 and the fault ws228 is chaotic, the strata fall in opposite directions, and the local uplift forms a graben style, which is easy to transfer and adjust the displacement. The major faults and the surrounding faults constitute a complex "Y" shape, showing the characteristics of torsion and tension.

The area near the transfer zone is favorable for hydrocarbon accumulation. Connecting faults play the role of lateral sealing of oil and gas. The development of fractures around the connecting faults provides a channel for the upward dominant migration and accumulation of oil and gas. The development position of the transfer zone becomes a local structural high point, and the oil and gas are transported to both sides of the transfer zone, forming a shielding trap on the hanging wall of the fault in the third member of Weizhou formation.

2.2.2. approaching transfer zone. It is composed of two or more faults which are close to each other in the head and tail. In the development position of approaching type, the strata are often cut and fall step by step, and the strain and displacement are regularly transferred along the tilt direction of the strata. The reflection layer on the seismic section is chaotic, showing the phenomenon of "like broken, like connected". The typical approach syntaxic transfer zone in the study area is composed of faults ws175 and faults ws219 (figure 4d), and the terrain is relatively high. In plane, the major fault extends in nee direction, and the dip end is curved and close to each other. On the seismic profile, major fault dip southward, which are similar to steps in shape, with basically the same occurrence and similar development scale(Figure 4d).

Fault ws175 and fault ws219 are the main control faults formed in the typical strike slip environment. The fault sealing is good, and several independent fault blocks are separated in the transfer zone. Fault ws219 is developed in the high part of the structure, and the transfer slope is the dominant oil and gas migration channel. During the reservoir forming period, it is blocked by the major fault and easy to accumulate in the down plate of the fault.
2.2.3. Single line collateral transfer zone. It is developed by a fault which dip changes along the strike, and the plane distribution pattern has no obvious change. Along the transfer zone, the terrain gradually decreases from east to west. In the middle segment of fault ws235, the fault is divided into two parts, which are finger shaped and interlaced with each other, and then the two faults are combined into one. The single line transfer zone realizes the displacement and deformation transfer within a fault, and has weak control and transformation ability for the surrounding structural zone. The seismic profile (figure 4e) shows that the East and West segments of ws235 fault are closely integrated. In E-E' section, the ws235 fault inclines northward and forms a horst with the south fault. In F-F' section, four faults a, b, c and d are developed in opposite directions, forming a horst, and the strata on both sides fall in turn. In section G-G', the major fault and the southern fault form a stepped style, and the faults fall to the south in turn. From west to east, the fault assemblage of ws235 gradually transits from horst graben assemblage style to ladder style, showing a unified fault system formed by tension and torsion. Therefore, the east and west parts of the fault ws235 should be one fault, the extensional deformation can be controlled and regulated by four finger shaped regulating faults in the middle of the major fault. The oil and gas transfer zone of fault ws235 is mainly controlled by the West strike slip zone, the oil and gas transfer zone is dominated by the West strike slip zone.

2.2.4. turning transfer zone. It is controlled by a single major fault. The curved part of the major fault produces several adjusting faults. The common plane distribution pattern is horsetail. The turning...
transfer zone is located in the south of the area, which is composed of fault ws221 and three nearly NE trending regulating faults (Figure 4f). The fault ws221 is close to the boundary fault 7. Under the influence of the ascending and descending movements of the upper and lower walls of the boundary fault and the NE strike slip in the area, the strata on one side of the descending wall of the fault ws221 deform and form three nearly parallel and consistent echelon adjustment fault layers with the strike of ws222, ws223 and ws224. The tail end diverges outward, the head end converges to the turning end of the major fault, it can adjust the fault distance and height difference in the NW direction of the north and the NW direction of the east of the major fault to achieve the conservation of strain. On the seismic profile (figure 4f), the transfer fault and the major fault are obliquely intersected, and they all incline to the south. The strata fall to the south in turn, and the displacement and deformation are regularly adjusted along the direction of vertical fault distance increasing.

3. Results & Discussion

3.1. The distribution of transfer zone

The development scale and location of the transfer zone generally depend on the regional tectonic background and boundary control conditions; the type of the transfer zone depends on the tectonic stress conditions of the major faults, the geometric characteristics of the faults and their relationships[5]. According to the analysis, it is considered that the transfer zone of WSG has the following distribution rules:  there are obvious differences in structural styles and basement subsidence on both sides of the transfer zone, which often constitute the plane of regional structure dividing line: take the fault ws229 and fault 227 as the boundary (figure 4b), the faults in the south are mainly NEE, NE and SE, and the faults in the north are NE or EW;  the structural background and boundary control conditions determine the type of the transfer zone;  The connection mode between different reflectors in the same transfer zone changes from soft connection to hard connection, and the connecting faults from deep to shallow increase obviously (figure 5): the transfer zone of Weizhou formation is more developed, and the number and amplitude of displacement transfer in the third member of Weizhou formation (T72) is larger; the transfer zone from the first member of Weizhou formation (T60) to Xiayang formation is less developed. From deep to shallow, the change of regional stress field makes the development and evolution of the transfer zone present the characteristics of coexistence of inheritance and transformation, extension and strike slip superposition, the type and structural style of the transfer zone formed by the same group of faults change.

3.2. Formation mechanism

Combined with the tectonic background of each period and based on the analysis of its evolution stage, the formation mechanism of the transfer zone in the study area is divided into time and space two types.

(1) The formation mechanism in time. Under the combined action of the strike slip activity of Ailaoshan-Honghe fault, the tensile stress[6] generated by the expansion of the South China Sea and the mantle upwelling, a regional stress field with strike slip and extension coexisting is formed. There are differences in the strength of strike slip and extension in different periods, and the stress background in different sedimentary periods. The development of the transfer zone is controlled by different forces.
Figure 5. WSG Geological profile characteristics (the location of the line is shown in Figure 2b).

(2) The formation mechanism in space. a. The pre-existing structure laid the foundation for the formation of the transfer zone: the activity of the pre-existing faults largely determined the characteristics of the development of the subsequent faults. A series of NE trending fault zones developed in Mesozoic era, which played a certain role in hindering the formation of the transfer zone laterally. With the change of the extension direction of the fault, the displacement and deformation transmission mode of the fault changed, thus controlling the formation and extension of the transfer zone. The movement and its position change in space. b. Segmented growth of faults is the direct reason for the formation of the transfer zone: from the period of initial tension to the period of sag rifting, the same fault generally goes through the isolated growth stage, "soft connection" stage and "hard connection" stage of connecting fault development, and the structural transfer zone is easy to occur at the position of fault overlap or the maximum displacement of fault.

Specifically: The stage of strong tension weak left lateral strike slip superimposition: the left lateral strike slip of Ailaoshan-Honghe fault was gradually strengthened due to the collision of Indosinian plate, the mantle upwelling was still strong. A tensile conjugate fault system with needxial strike slip and NW sinistral strike slip was formed\(^7\) (figure 6a). At this time, the dominant activity of basement fault is still strong, and the growth of partial fault displacement is hindered. Fault 7 moves along the strike in segments. The eastern overlapping control fault ws227 is formed, the collateral type major fault grows in segments, and the fault ws229 is basically developed and formed; the main body of the southern turning control fault ws221 is initially on the scale. ② The stage of weak extension strong dextral strike slip superimposition: the strike slip of Ailaoshan-Honghe fault was strengthened, the mantle upwelling was weakened. While inheriting the previous activity, the NW trending strike slip fault splits into a series of collateral transfer zone (figure 6b). Due to the influence of pre-existing structures, the strike displacement stops when it reaches the fault ws225. In the southern part of the fault ws221 developed several minor faults under the stress of torsion and tension, while fault ws235 underwent structural inversion deformation under the influence of compressive stress, forming a single line collinear transfer
zone.

Figure 6. Simplified models showing fault geometries during (a) The third member of Weizhou formation and (b) Xiayang formation time in the study area. QXU-Qixi Uplift; The small blue and purple arrows represent the extension and strike slip directions of faults or strata respectively.

4. Conclusions

Through the quantitative statistical analysis of the transfer zone structure in the study area, we can better understand its specific characteristics and development trend.

(1) The structural stratigraphic structure of WSG changed from Eocene to Oligocene, forming a S-type fault system with opposite dip, which may be related to the change of principal stress direction. According to the two different tectonostratigraphic structures and fault systems in Eocene and Oligocene sequences, the two-stage transition zone is determined. In the third member of Weizhou formation (T72), which are collateral, overlapping, approaching, turning and collinear. In the Xiayang formation (T60), collateral and overlapping transfer zone are developed.

(2) Controlled by the tectonic background and boundary conditions, the distribution of the transfer zone is different. The transfer zone plays the role of dividing the structural zones. The fault strike on the plane and the fault structural style on the section are obviously different, and the transfer displacement mode and quantity of the transfer zone in different sedimentary periods are also obviously different.

(3) The characteristics of fault development in WSG are the reflection of extensional and extensional superimposition. The NE trending basement faults lay the foundation for the formation of the transfer zone. Under the combined action of Ailaoshan-Honghe fault strike slip, South China Sea expansion and mantle upwelling derived tension, the segmented growth of faults is the direct reason for the formation of the transfer zone. From deep to shallow, the transfer zone is characterized by the coexistence of inheritance and transformation, and the superposition of strike slip and extension.

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