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*Research Article*

# Structural Formation, Evolution, and Genetic Mechanisms of Fault in Controlling Hydrocarbon Migration of Unconventional Rocks: A Case Study of Zhuangnan Fault

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Zhuangnan fault zone was affiliated with Gubei subsag of the Zhanhua sag in Jiyang Depression, Bohai gulf basin. Zhuangnan fault zone has two functions as the main east-west strike-slip accommodation structure. That is, on the one hand, Zhuangnan fault zone inherited the rules of development of regional tectonic. On the other hand, the present structure framework of Zhanhua sag was reconstructed by Zhuangnan fault zone. In the study, there are four main seismic reflectors: T0, T1, T2, and T6. They are the basis for researching the planar and vertical features of Zhuangnan fault zone. The structural formation, evolution, and genetic mechanisms of Zhuangnan fault zone are studied from three aspects of geometry, kinematics, and dynamics. In geometry, by the closure interpretation of 43 south-north interpretation sections and 24 east-west interpretation sections, the result indicates that Zhuangnan fault zone has its special regularity and characteristic which has three-piece planar characterization (eastern part, middle part, and western part). Three types of plane combination forms are determined: arched, linear, and "S" curved type. The plane combination structure styles of the Zhuangnan fault zone mainly include feather row, horsetail, grid, diagonal, and parallel style. These planar structural features play an important role in indicating the fault zoning of Zhuangnan fault zone. Based on the plane and section structural styles of Zhuangnan fault zone and the analysis of dynamic evolution, it is found that Zhuangnan fault zone has a succession relationship between deep and shallow fault systems. From tectonic evolution and regional dynamic point of view, this paper discusses the activity law of the Zhuangnan fault zone and the boundary faults on the east and west sides of Jiyang Depression, which are Changdi fault, Wuhaozhuang fault, and Chengnan fault, respectively. This study provides a new and more reasonable explanation for the unique structural characteristics of Zhuangnan fault zone and further confirms the important role and regulation mechanism of Zhuangnan fault zone.

## 1. Introduction

In recent years, the fine characterization of tectonic features and the relationship between fault evolution in the evolution of the rift basin have been the focus of the research work of scholars at home and abroad [1–3]. Faults are relatively developed in the eastern part of Jiyang Depression. The faults are generally developed in east-west, north-east, and northwest strikes. Zhuangnan fault zone is a secondary structural belt of Zhanhua sag in Jiyang Depression [2, 4, 5]. It is an important readjust fault zone which fault strike is EW. There are also a group of faults which fault strike is SN, among which Changdi fault, Wuhaozhuang fault, and Chengnan fault are the main boundary faults of Zhanhua sag. The strike-slip structural patterns, active rates, and time of these faults have been studied extensively [6–8]. These faults have an important influence on the accumulation process in this area. Therefore, researchers have paid much attention to the formation age, tectonic properties, and dynamic mechanism of faults in this area. It is generally

believed that the fault assemblage of Zhuangnan fault zone communicates the connection between the lower source rock and the upper reservoir. As an important hydrocarbon transport channel, it creates favorable conditions for hydrocarbon accumulation in the upper Ng and Ed Formations [6, 9, 10].

However, due to the complex secondary structure and fault effect of the strike-slip adjustment fault zone, there are still many problems in Zhuangnan fault zone that need further study [11]. The geometric characteristics of Zhuangnan fault zone need to be carefully described [9]. The inheritance characteristics and details of Zhuangnan fault zone need further analysis [10]. As for the formation mechanism of Zhuangnan fault zone, especially the adjustment mechanism between Zhuangnan fault zone and boundary faults, what kind of dynamic factors are still needed to be studied?

In this paper, the geometric characteristics, tectonic evolution, and adjustment mechanism of Zhuangnan fault zone are studied using the latest 3D seismic data of Zhuangnan fault zone in Jiyang Depression which are carefully interpreted and combined with a high-resolution coherency analysis technique. In addition, the formation mechanism of the NS-trending strike-slip faults and the EW-trending strike-slip adjustment fault zone in the east of Jiyang Depression, represented by Zhuangnan fault zone and its boundary faults (Changdi fault, Wuhaozhuang fault, and Chengnan fault), is further analyzed.

## 2. Regional Geological Outline

Zhuangnan fault zone is a secondary structural belt of Zhanhua sag in Jiyang Depression. Zhuangnan fault zone was composed of a nearly west-east strike listric normal fault and the subfaults derived from the main fault. Zhuangnan fault zone is bordered by Chengdong fault on the west and the Wuhaozhuang fault and Changdi fault on the east (Figure 1). Four oilfields were developed in Zhuangnan fault zone, which were Zhuangxi oilfield, Wuhaozhuang oilfield, Changdi oilfield, and Laohekou oilfield. Those oilfields consist of many oil-bearing strata, which are distributed in the Archaeozoic, Palaeozoic, and Mesozoic and included some reservoirs buried deeply [7, 12–15]. Paleozoic buried hill reservoir is the most important oil pool types in Zhuangxi oilfield. Major exploration targets of Wuhaozhuang oilfield, Changdi oilfield, and Laohekou oilfield are reservoirs in the Cenozoic (Steven 1999) [3, 16].

All four oilfields are the typical complicated fault-block oilfields in east China. They have more styles and more complex forming causation types. At present, Zhuangxi oilfield relies mainly on structure reservoir; Wuhaozhuang oilfield is dominated in composite structure-lithology reservoir [4, 17] (Shamik 2010). Changdi oilfield is complicated by many faults and belongs to anticline reservoir having multilayer of sands, which is divided into two tectonic types: Paleozoic buried hill structure and Mesozoic draping structure. The main accumulation model of Laohekou oilfield in upper Guantao formation is the lithologic oil and gas pools [5, 6, 8, 18].

## 3. Structure Types

Applying three-dimensional seismic data, geological data, and logging data, we analyze and describe the structural feature and fracture feature of Zhuangnan fault zone. Geoframe 4.3 seismic interpretation software has been applied to seismic layer labeling and making synthetic seismogram, coherent data analysis, and seismic explanation [8, 19, 20], by making synthetic seismic records of well data of test wells, a fine horizon calibration for the target strata. By accurately interpreting with a 3D coherence analysis and seismic section in plain, section, and space, the geometry characteristics of Zhuangnan fault zone have preliminarily been understood. The application of coherent data volume to interpret fault blocks in complex fault block areas is a very effective tool [9, 13, 14, 21] (Alissa 2009). The time slice of a coherent data body can unveil the direction of the Zhuangnan fault zone generally, the configurations of faults in both areal and vertical directions, and guidance-find the secondary fracture. Considering most of the faults in Zhuangnan fault zone are nearly west-east strike, the east-west interpretation section should be the one that supplements a focus on the south-north interpretation section (Feng 2013).

*3.1. Vertical Fault Assemblage.* The closure of intersecting geophysical information has been an important problem in geophysical data interpretation. By the closure interpretation of 43 south-north interpretation sections and 24 east-west interpretation sections, the article summarized fault growth in Zhuangnan fault zone below. Zhuangnan fault zone had developed on the tectonic background of Zhuangnan buried hill. The fault zone has the characteristic of plastic uplifting by reason of the spreading function and antithetic drag of the main faults in Zhuangnan fault zone. The study found that Zhuangnan fault zone had the characteristics of more active faults developed on both sides of the fault zone than the middle part of the fault zone. And the faults were concentrated developed in the north of the area.

From that, we divided Zhuangnan fault zone into three parts: western part (line: 1371-1450), middle part (line: 1450-1650), and eastern part (line: 1650-1791).

*Western part*: the evolution of Zhuangnan fault zone experiences three stages. With four listric faults trending NEE, dipping S developed of early evolution, those faults are arranged in equivalence and parallelism. Fault styles are mainly step faults. Those faults have long fault displacement, which can cut the overlying formations and basement strata.

In the median period of development, four secondary fractures dipping north were developed. Those faults ending on the listric faults dipping S are located on the southernmost part of the four listric faults.

Those secondary fractures are arranged in equivalence and parallelism. Fault styles are mainly step faults. The median period subordinate structure fault and the early main faults display a “y” character form fault array in profile. Fault styles are mainly graben and step fault. Those secondary fractures also have long fault displacement, which mainly cut the overlying formations.

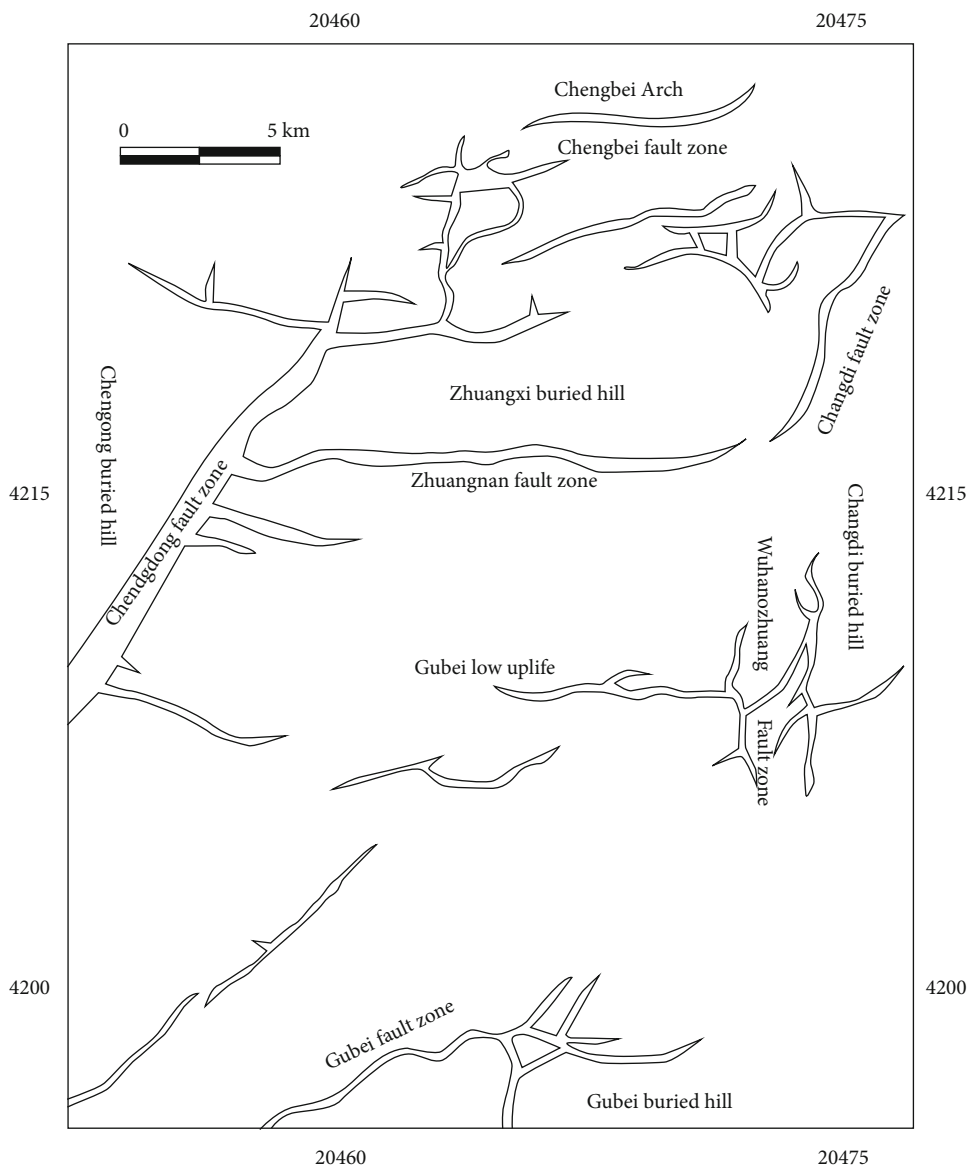


Figure 1: Structural position of Zhuangnan fault zone.

The late development faults grow on the four secondary fractures of median period development, which displayed an "anti-y" character form fault array with median development faults in profile. The late development faults have short fault displacement, which only cut the shallow formation (Figure 2 and Table 1).

*Middle part*: most early development faults gradually cease their activity, which only cut the basement strata. The activity of Zhuangnan fault is always persisted. Zhuangnan fault becomes the most important fault dipping S which section shape is listric. The gradient of Zhuangnan fault slackens from the top down. Zhuangnan fault cuts the basement strata. The subsidiary shear fractures complicate the overlying formations. The major "y" character form fault array in the studied area was composed of Zhuangnan fault and one secondary fracture in dipping N. Three stages of secondary fracture evolved between them. The combinations of the faults of different phases are "y" character form and "anti-y" character form. Overall, the middle part of the structure possesses the characteristic of faults in the overlying formations which are more complex than that in the basement strata (Table 2).

*Eastern part*: the eastern part is the activity of early development fault enhancement. Three-fifths of early development faults cut the overlying formations and basement strata, and two-fifths of early development faults cut the basement strata, which do not cut the overlying formations. Four secondary fractures dipping north were developed in Cenozoic strata. There is a strong symbiotic relationship between the main faults of F1, F3, and F5 and the secondary fault of F2. F2 fault was cut by F1 fault, displaying "y" character form fault array in profile with F1 and F3 faults. F4 fault was the late development fault, displaying "y" character form with main faults (Table 3).

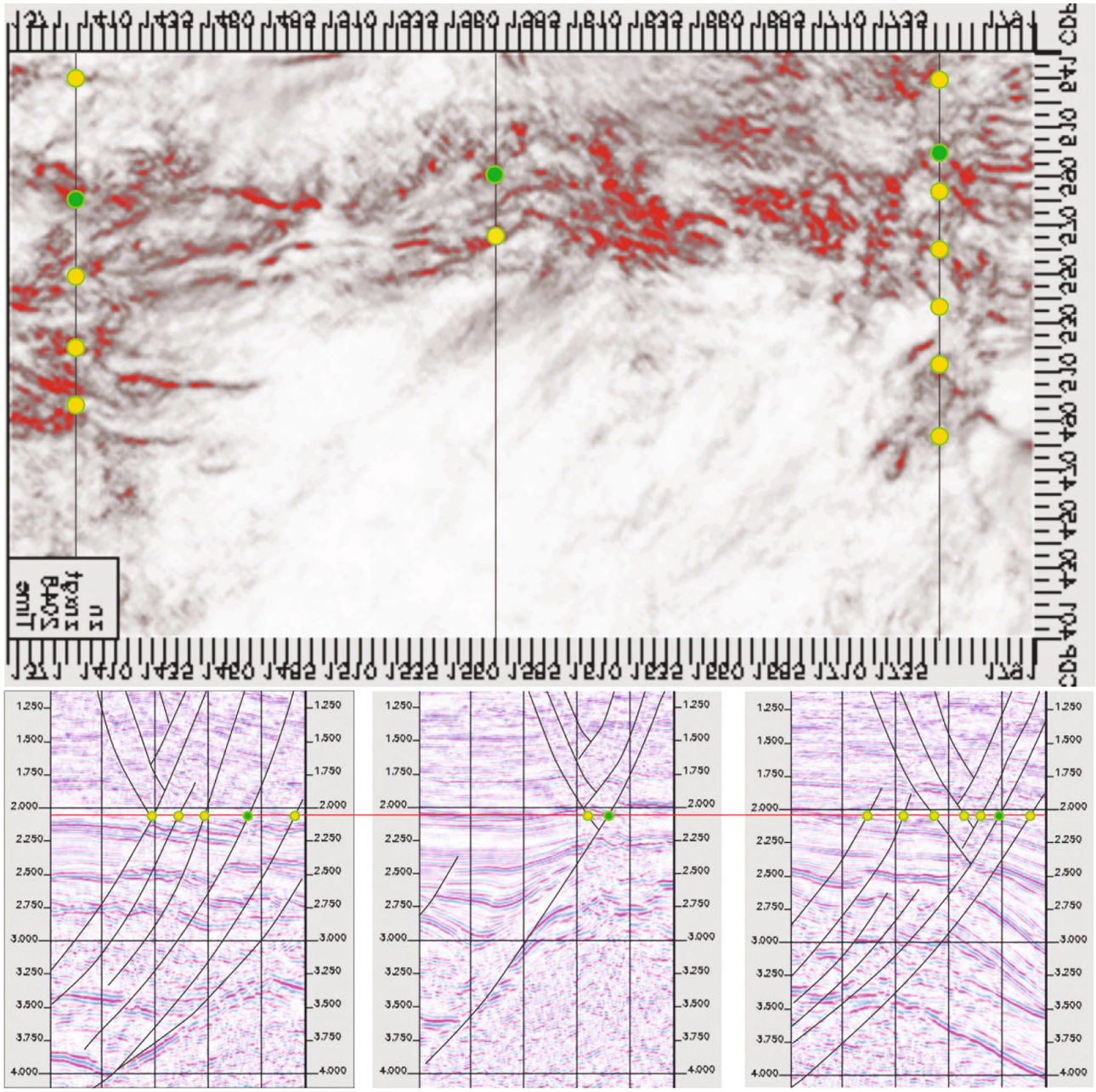

Figure 2: Fault interpretation on coherent slice and seismic time slices.

Table 1: Major fault elements of the western part.

| Fault | Fault strike | Dip directions | Fault dip | Fault displacement (m) | Extended length (km) | Section shape |
|---|---|---|---|---|---|---|
| F1 | NEE | S | 35-70 | 500 | >8 | Listric |
| F2 | NEE | N | 45-60 | 200-300 | 4 | Platelike |
| F3 | EW | S | 40-50 | 300-400 | >8 | Listric |
| F7 | NWW | S | 40-50 | 100-200 | 3 | Listric |
| F8 | NEE | S | 45-60 | 100-200 | 2.5 | Platelike |
| F9 | NEE | N | 45-60 | 100-200 | 2.5 | Platelike |
| F10 | NEE | N | 40-50 | 100 | 2 | Platelike |

Table 2: Major fault elements of the middle part.

| Fault | Fault strike | Dip directions | Fault dip | Fault displacement (m) | Extended length (km) | Section shape |
|---|---|---|---|---|---|---|
| F1 | EW | S | 35-70 | 500 | >8 | Listric |
| F2 | EW | N | 45-60 | 200-300 | 4 | Platelike |
| F3 | EW | S | 40-50 | 300-400 | 5 | Platelike |
| F4 | NWW | N | 40-50 | 100-200 | 3 | Platelike |
| F6 | EW | N | 45-60 | 100-200 | 5 | Platelike |

Table 3: Major fault elements of the eastern part.

| Fault | Fault strike | Dip directions | Fault dip | Fault displacement (m) | Extended length (km) | Section shape |
|---|---|---|---|---|---|---|
| F1 | NEE | S | 35-70 | 500 | >8 | Listric |
| F2 | NWW | N | 45-60 | 200-300 | 4 | Platelike |
| F3 | NWW | S | 40-50 | 100-200 | >8 | Platelike |
| F5 | NEE | S | 45-60 | 100-200 | >8 | Listric |

*3.2. Characteristics of Plane Faults and Plane Fault Combination.* By tracking the four selected main seismic reflection horizons T6, T2, T1, and T0, the interpretation of plane faults in the main horizons of the study area is finally completed, combined with the explanation of the section fracture and the fracture characteristics displayed in the coherent body slices along the layer. The characteristics of plane fracture combination of main horizons, such as T6, T2, T1, and T0, are shown in Figure 3.

*3.2.1. T0 Reflector.* The morphologies of the three main fracture planes are mainly arched bending. The fault strikes nearly east-west and arches upwards northward in the middle of the fault zone. The relationship of the plane combinations is a parallel arrangement. The secondary faults strike nearly northwest-west, and most of them are linear, and some of them are curved. The strikes between the secondary faults are nearly parallel, and they are obliquely intersecting with the main faults, which mostly occur in the bending deformation parts of the main faults. The overall fracture pattern of the T0 reflector is shown as a grid-like combination (Figure 3).

*3.2.2. T1 Reflector.* Fractures gradually decreased in the middle part, and the main fracture form was still arched. The secondary faults that are opposite to the main fault have the same overall trend as the main fault, which is a parallel combination. There are secondary faults on both sides of the fault zone, and secondary small faults develop at the eastern end of the antithetic fault, which intersect with a small angle and parallel to the Zhuangnan fault. There are many small south-dipping faults in the south of the antithetic fault, all of which have the same trend as the Zhuangnan fault, which are linear and parallel combinations. In the western part of the fault zone, there exist six secondary faults with curved shapes and the same trend. The two small faults in the southernmost area extend shorter, and the two faults have an echelon-like arrangement. The T1 reflector fault system appears as a parallel combination mode as a whole (Figure 4).

*3.2.3. T2 Reflector.* The width of the main fault, the Zhuangnan fault, gets obviously wider than that of the overlying reflectors T0 and T1, which reflects the slowing downtrend of the slope of the fault zone, and its profile shape turns into a shovel shape. The strike is nearly east-west, and the central part bends northward. The volume of the secondary faults becomes smaller, and the extension length is shortened. They mostly occur in the east and west of the fault zone and parallel to the main fault. There are three secondary faults in the northern part of the main fault, which are not continuous with each other and tend to be in en echelon arrangement. The southern faults are scattered, and two northeast-trending faults in the west are arranged in parallel with a northeast-trending fault in the east. Two secondary faults in the lower part develop in the central-southern and southeastern part of the fault zone, which strike NWW and are arranged in parallel. The secondary fractures of the T2 reflector and the main fault are in parallel combinations. The development positions of the secondary faults are scattered, and the strikes are not all the same: some are en echelon combinations, and some are parallel-type combinations (Figure 5).

*3.2.4. T6 Reflector.* The fault width of the main fault becomes wider, indicating that the slope of the fault continues to decrease, and the shovel shape of the profile becomes more prominent. The combined relationship between the Zhuangnan fault of the main fault and the secondary fault is more complicated. The western region is mainly a parallel combination mode. The small southern fault end adjacent to the main fault has developed secondary faults, showing the characteristics of stress release at the fault end. A fault, which is derived between the eastern part of the fault zone and the north part of the leading fault, intersects with the main fault at a small angle, gradually extends westward, and parallels to the main fault. Two south-dipping faults have also developed in the north, and their strikes are consistent with the main fault. A secondary fault is derived from the extension direction of the curved part in the middle of the main fault, and a number of divergent small faults develop at the end.

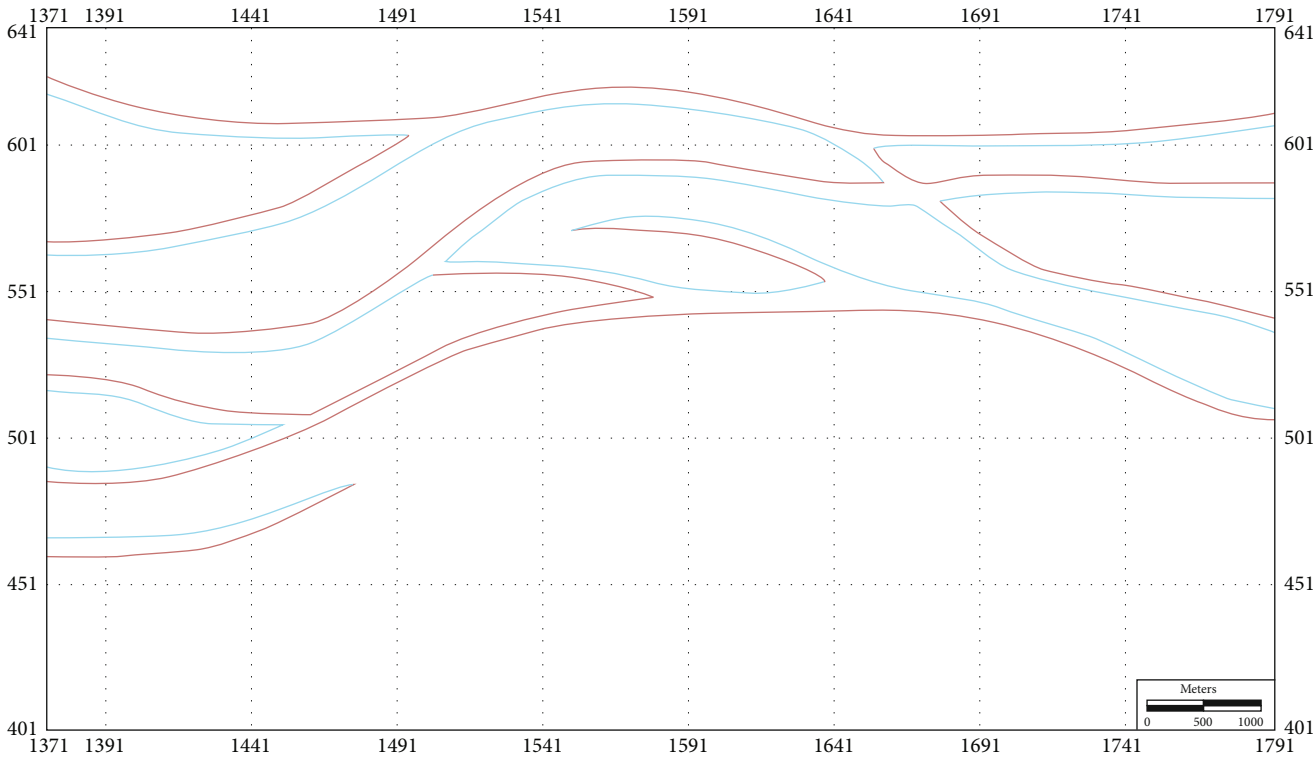


Figure 3: T0 reflector plane fracture system.

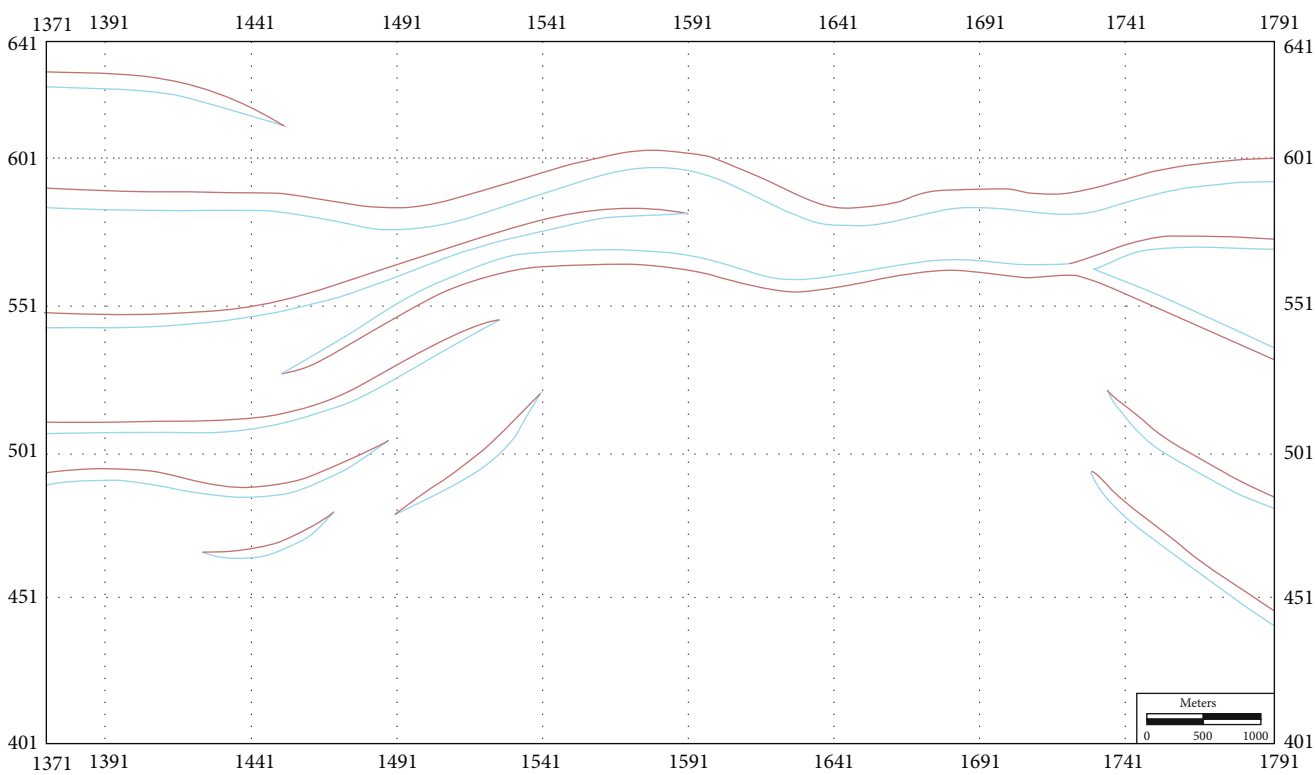


Figure 4: T1 reflector plane fracture system.

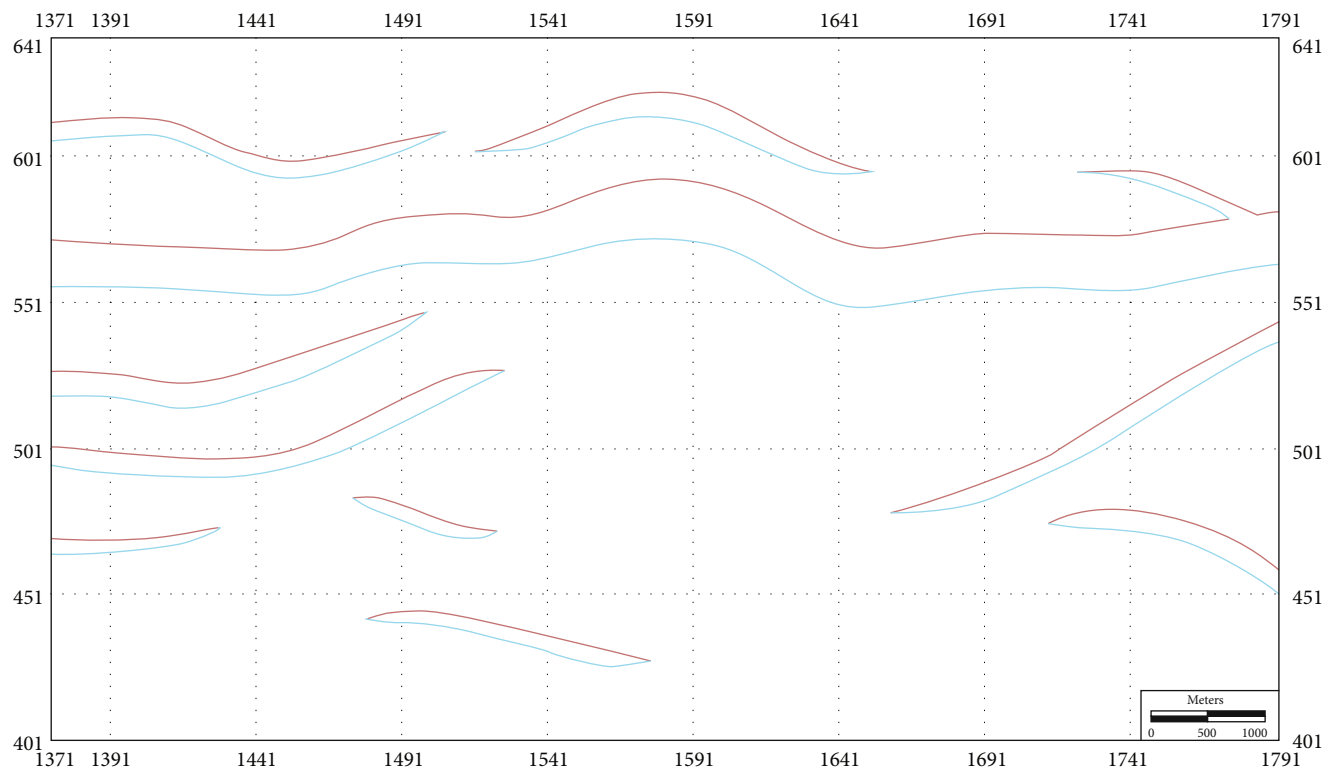


Figure 5: T2 reflector plane fracture system.

On the east side of the extension fault, there exist two secondary faults arranged in parallel with the main fault; on the west side of the extension fault, there are two NEE inclined secondary faults. The T6 reflector layer appears as a parallel combination mode as a whole, and there is a combination mode in the Chinese character "enter" at the tail end of both the main fault and the secondary fault (Figure 6).

After research, the characteristics of the main fault and the secondary fault are summarized as follows:

*The characteristics of the main fault*: the main fault is the Zhuangnan fault (F1). The Zhuangnan fault, the southern boundary fault of the Zhuangxi buried hill, controls the Meso-Cenozoic sedimentary, plays a role in connecting the tertiary oil source and the buried hill reservoir, and is of great significance to the accumulation of the Zhuangxi buried hill. From the data collected and processed, it is observed that the fault displacement from top to bottom in the study area gradually grows. According to the observation of the extension of the fault from the seismic profiles, the shovel shape of the fault in the Zhuangnan buried hill site has gradually steepened, which may be one reason for the increase in the fault displacement. However, in the upper part of the fault zone, there are multiple secondary faults, and the fault tendency is basically the same. There are three main faults in the same direction (F3, F5, and F7) associated with the Zhuangnan fault. In the seismic profiles, the four faults are equally spaced and arranged in parallel. The F3 fault has a longer extension distance, which is parallel to the Zhuangnan fault. The F5 fault develops in the eastern and western sections of the Zhuangnan fault zone, but its western side intersects with the antithetic fault F2, and the eastern section intersects with F3, the same direction fault. The F7 fault develops in the west wing of the Zhuangnan fault zone with a shorter extension distance and intersects with the main fault. Compared with the development of faults in other depth ranges, the three main faults mostly concentrate on the eastern and western edges of the Zhuangnan fault zone, and the central parts do not develop or only extend to the basement fault, and some of the faults do not cut through the overlying strata.

*Characteristics of secondary faults*: in summary of the characteristics of the seismic reflection profiles of each segment of the faults, the most important antithetic secondary fault is the F2 fault. The antithetic secondary faults mainly develop on the top reflector of Ed3, which can cut through the Guantao formation. When it comes to the shallow part, the amount of secondary faults gradually becomes larger and divergent. The cross-sectional characteristics of the secondary faults such as F2, F4, and F6 are shown as a step-like combination. In the plane combinations, the F4 and F6 faults extend for a short distance, and they intersect in a plume shape along the bending tangent of the F2 fault. The combination relationship between the secondary fault and the main fault is mainly the "y" shape combination and the reverse "y" shape combination; the plane combinations mainly include parallel stepped combination and grid-like interweaving (Figure 7).

By analyzing the combined patterns in space of Zhuangnan fault zone, the morphology of the Zhuangnan fault zone is characterized by gentle at the bottom and steep at the top, showing the characteristics of listric fault. The lower flat area

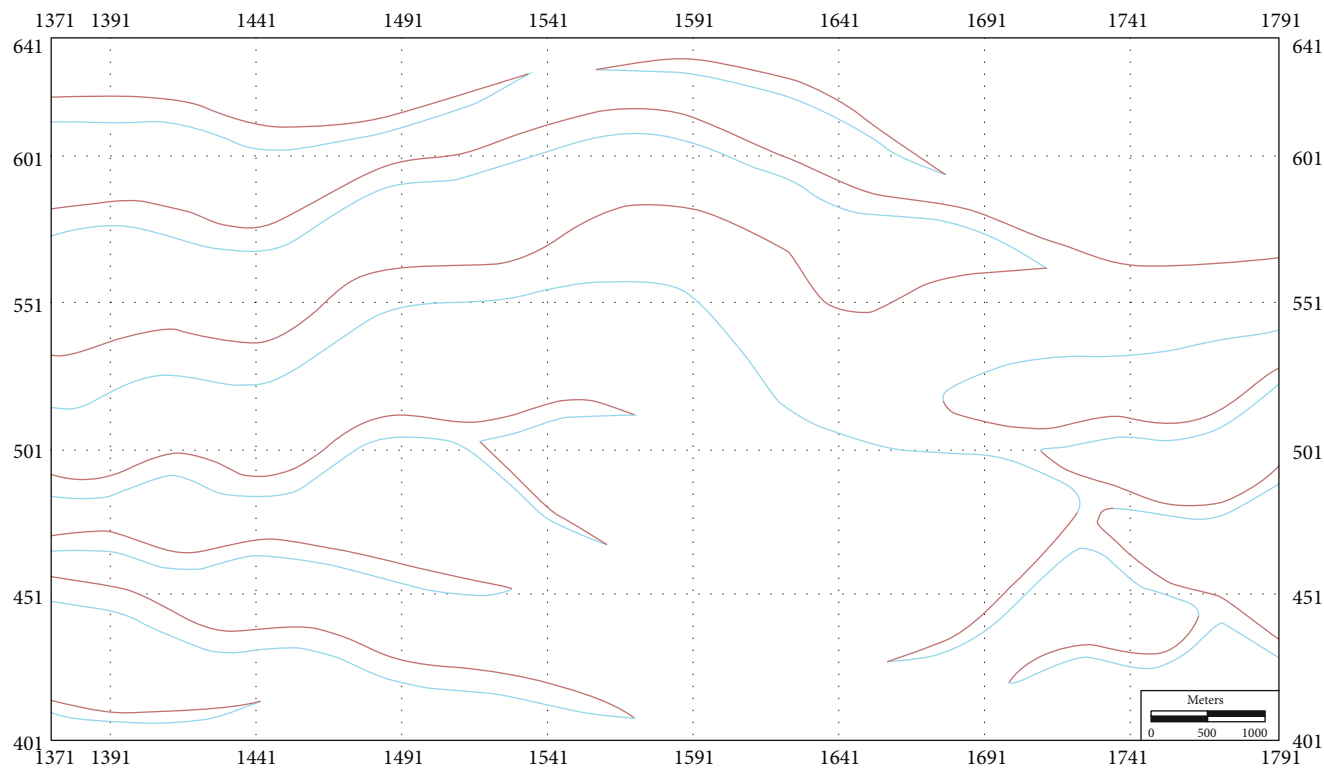


Figure 6: T6 reflector plane fracture system.

of the listric fault has experienced strike-slip shear. Secondary faults located in shallow layers are more developed, which is the result of equilibrium stress release. The plane combination structure styles are as follows: feather row, horsetail, grid, and diagonal. The Zhuangnan fault zone had the characteristics of more active faults developed on both west and east parts of the fault zone than the middle part of the fault zone. The faults developed in the middle part line up in parallel. This feature indicates that the Zhuangnan fault zone is greatly influenced by the adjacent faults on both sides and gradually extends to the middle part of the fault zone, so the middle part of the Zhuangnan fault zone has relatively little influence.

*3.3. Structural Style Research.* American geologists Harding et al. (1979) and Lowell (1985) did systematic studies on structural styles and believe that structural styles refer to the overall characteristics of related structures with close ties in section morphology, plane distribution, arrangement, and stress mechanism and are a combination of structural deformation under the same stress environment, which is an organic combination of multiple related structures.

According to the morphology of the faults and the combination modes, the following five structural styles under the action of stress are summarized: extensional structural style, extension-strike-slip structural style, strike-slip structural style, extrusion-strike-slip structural style, and extrusion structural style. According to the main fault properties, geometric forms, and combination styles of the Zhuangnan fault zone, it is believed that there are two structural styles in the Zhuangnan fault zone: extensional structural styles.

There are two main types of morphology for the Zhuangnan fault section: plate type (flat type) and shovel type. The main fault section of Zhuangnan is shovel type—-the slope of the upper fault is steeper, and the lower part is slower. Other secondary and associated main faults are all planar. With the gradual increase in the degree of fault evolution, the fault plane generally evolves from the plate type to the shovel type and then to the sloping type. Affected by the characteristics of the near east-west trend of the Zhuangnan fault zone, the combination modes of the profile, mainly stepped fault combination and y-shaped fault combination, can be well observed in the north-south line profile of the Zhuangnan fault zone. The y-shaped fault is mainly composed of the Zhuangnan main fault and its southern secondary faults, which reflect the combined type of growth faults. Under the influence of the extension of the Zhuangnan fault, the hanging wall flexed. Stratum combination styles mainly include graben combination and step combination.

In the plane structure style, the Zhuangnan fault zone mainly strikes in EW direction, and the fault zone generally bends northward in the central area. Its plane geometry is generally arched, and the local forms mainly include linear, arc, and "S" curved type. Through the study of structural characteristics, it is concluded that the Zhuangnan fault zone has the structural characteristics of east and west segmentation. This feature is of great significance to the study of dynamic mechanisms, and it is very likely to represent the different stages of fracture reformation on both sides. The arched bending shape in the middle of the Zhuangnan fault zone is very special, which further reflects the difference in stress caused by the development of faults on both sides of

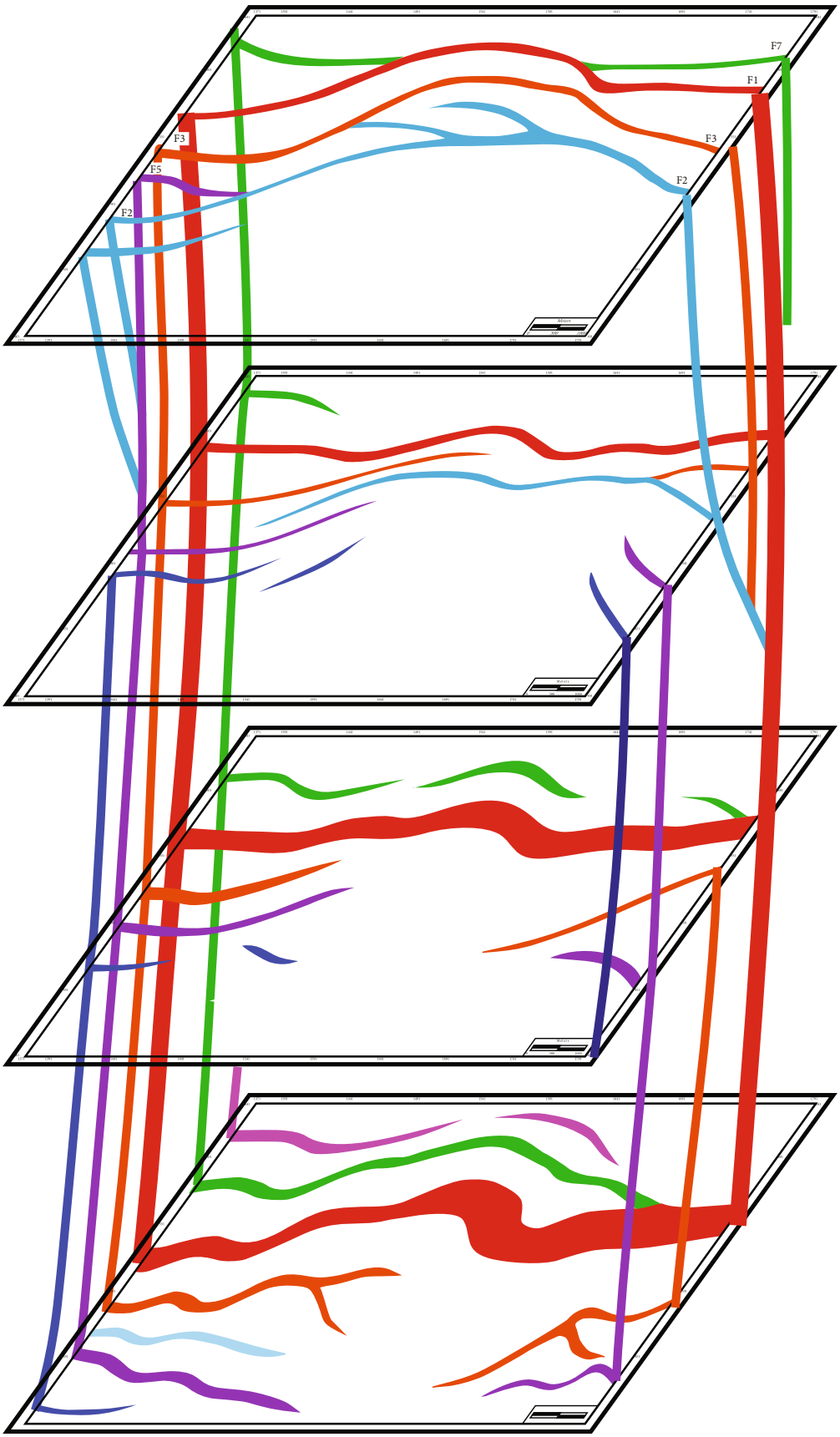


Figure 7: Combined patterns in space of Zhuangnan fault zone.

the east and west and is balanced by the bending deformation of the middle of the fault. This arched shape is an important structural phenomenon that adjusts the structural balance.

The plane combination structure styles of the Zhuangnan fault zone mainly include feather row, horsetail, grid, diagonal, and parallel style (Figure 8). Among them, the first three combined styles mainly appear in secondary fractures. Actually, the parallel combination mode and the oblique combination mode are the most important. The parallel combination model not only appears in secondary faults but also exists in the combination of the main secondary faults and the Zhuangnan main fault.Main faults through the Zhuangnan fault zone have a horizontally stretching distance. They are arranged parallel to each other and have arches bending in the middle part. There are also have the feather row combination which can reflect the strike-slip characteristics. The secondary faults and induced structures are located at the end of the main fault, and the plane combination structure styles are feather row, horsetail, grid, and diagonal (Figure 9). These combination structure characteristics are also an important basis for dividing Zhuangnan fault zone into three parts.

*3.4. Planar Fault Assemblage.* Three breaking with near E-W strike through the Zhuangnan fault zone have a horizontally stretching distance. They are arranged parallel to each other and have arches bending in the middle part.

Zhuangnan fault (F1) is the most important fault as the southern boundary fault of Zhuangxi buried hill and is also an important oil-controlling fault. From the collection and processing of data, the cause of Zhuangnan fault throw increasing from bottom to top was identified. It is because the dip directions of Zhuangnan fault are steeper above Zhuangxi buried hill.

Four synthetic faults are associated with Zhuangnan fault. They are F2, F3, F9, and F10. They are arranged parallel to each other and evenly spaced. In those four faults, F2 and F3 faults have a longer horizontally stretching distance than F9 and F10 faults. F9 and F10 faults are mainly distributed in the west area of the Zhuangnan fault zone.

Except for the associated faults, many secondary fractures derived from F1 fault and F2 fault were developed. The secondary fractures derived from F1 fault extended along the tangent to the bend deformation occurring on the middle part of Zhuangnan fault zone (F5 tangent to the main fault along the east and F7 tangent to the main fault along the west). And the "入" Chinese character form fault array was shaped with Zhuangnan fault. Three secondary fractures derived from F2 fault are developed between F2 and F3. They are arranged in echelon to each other and evenly spaced. The secondary fractures join with the F2 fault in bipenniform. The order of these secondary fractures is F6 to F4 and then F8 from east to west (Figure 2).

Two sets of faults provide the condition of shelter for hydrocarbon accumulation. The "入" Chinese character form fault array promoted formation of fault screened structure types of favorable traps from the hydrocarbon accumulation perspective. A large structural trap from the south of F2 fault is made up of buried hill draping structural belt and a sealing fault cutting the draping anticline (Figure 10).

The analysis of the geometrical characteristics of Zhuangnan fault zone leads out the following rule: the structural pattern of Zhuangnan fault zone is normal fault assemblage. Zhuangnan fault zone has two main section structure patterns, stair-step shape structure pattern and composite "y" character form structure pattern. Parallel is the main plane structure pattern; the bipenniform structure pattern characterized by strike-slip is the important supplement plane structure pattern. The evolution of Zhuangnan fault zone is under the extensional and shear stress field environment.

We need an in-depth study of geological evolution and dynamics of Zhuangnan fault zone on the basis of geometrical characteristic study.

## 4. Tectonic Evolution and Regional Dynamics

Through the structural interpretation and analysis of the section, the structural style of the Zhuangnan fault zone is discussed: the fault type of the Zhuangnan fault zone is mainly a combination of normal faults, and the structural style of the section is mainly a combination of stepped faults and "y"-shaped faults. The plane structure is mainly parallel, and there are also diagonal combinations that can reflect the characteristics of strike-slip. The main stress characteristics of the overall structural style are tensile stress and shear stress. As a result of the experience of superposition and reformation of multiperiod tectonic movements, the structural style of the Zhuangnan fault zone is complicated. The Zhuangnan fault zone has experienced three stages of tectonic movement and two stages of tectonic transformation. The three phases of tectonic movement are Indosinian movement, Yanshan movement, and Himalayan movement. The two tectonic transition stages are Late Indosinian-Early Yanshan, corresponding to the Middle Triassic-Jurassic-Early Cretaceous, the stress field transforms from compression to extension; Late Yanshan-Early Himalayan geology chronologically corresponds to the Late Cretaceous-Paleo-Modern, the stress field transforms from left-handed stress to right-handed stress [46-51]. When the tectonic transition periods of the two fault zones are compared, certain inheritance and transformation characteristics can be found between the two. It is of important guiding significance for the study of the formation mechanism of the Zhuangnan fault zone to make full use of this feature.

The study of regional dynamic mechanism helps to get a clear understanding of the evolution background of the Zhuangnan fault zone, which is of great significance for our accurate understanding of the structural characteristics of the Zhuangnan fault zone, which are always inherited and innovative. In the study of the structural characteristics of the Zhuangnan fault zone, it is shown that the Zhuangnan fault zone has the characteristics of a three-segment distribution in the east, middle, and west segments. The east and west segments have similar fracture characteristics and are more complex than the middle segment. These features all reflect its important characteristics as a regulating fault,

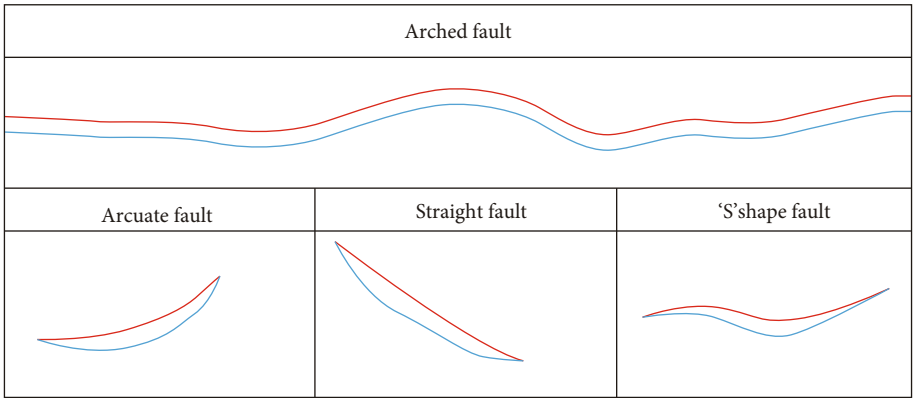


Figure 8: Four types of plane faults in Zhuangnan fault zone.

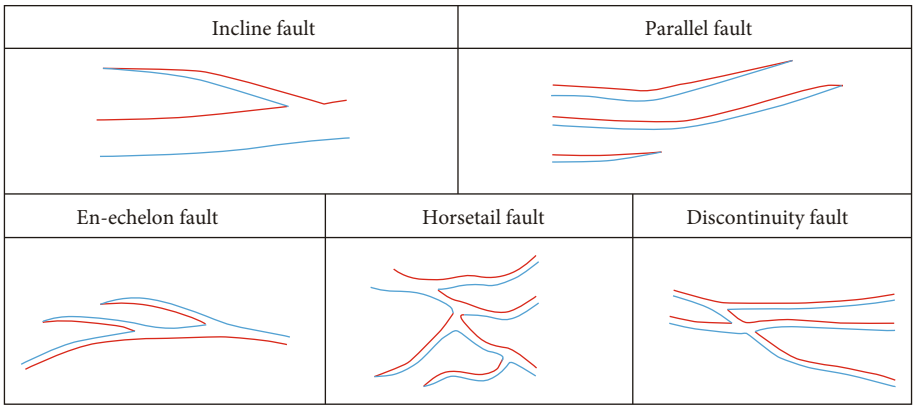


Figure 9: Five types of plane combination structure in Zhuangnan fault zone.

which is significantly affected by the main faults on the east and west sides and has a noteworthy reforming effect on the faults on both sides.

First, calculating and analyzing the activity of the main faults on the east and west sides of the Zhuangnan fault zone contribute to the study of the inheritance relationship between faults. The west side of the Zhuangnan fault zone is mainly the NNE-trending Chengdong fault, and the two main faults on the west side are the NEE-trending fault, the Changdi fault, and the NW-trending fault, the No. 5 pile fault.

Zhuangnan fault zone is an important west-east strike structural belt of Zhanhua sag. The geological evolution and dynamics of it are closely related to the evolution and dynamics of Zhanhua sag. The activities of Tan-Lu fault zone have a significant impact on the east of Zhanhua sag.

The extending direction of faults in Zhuangnan fault zone is consistent with the strike of major faults of the western branches of Tan-Lu fault zone and Lai-xi fault. The strike-slip structural style occurs vertically as echelon faults in the east of Zhuanghua sag like Changdi fault, Gudong fault, and Kendong fault and faults in the west like Chengdong fault, Yidong fault, and Yinan fault. Fault strike is NNE or nearly NE. Those faults controlled the distribution of Meso-Cenozoic strata and the development of the tectonic. Zhuangnan fault zone is located between Changdi fault and Chongdong fault. Fault strike is EW. Zhuangnan fault zone is the accommodation zone with other faults which strike is EW, nearly NE, and NW in Zhuanghua sag. Zhuangnan fault zone has the characteristics of longer horizontally stretching distance, large fault throw, and long active time whose active lives covered the period from Mesozoic to Neogene, which controls the sedimentation, tectonic evolution, and oil-gas accumulation in Zhuanhua sag. Geological evolution and dynamics of Zhuangnan fault zone are closely related to the activity of the three boundary faults (Chengdong fault, Changdi fault, and Wuhaozhuang fault).

Zhuangnan fault zone reached Chengdong fault in western Zhanhua sag and joined Changdi fault in eastern Zhanhua sag. Wuhaozhuang fault developed on the southeast part of Zhuangnan fault zone (Figure 11).

In the structural pattern of Zhanhua sag, Wuhaozhuang fault, Guxi fault, and Luoxi fault which fault strike is NW are arranged in echelon to the left row from north to south. These features clearly reflect the left-lateral strike-slip character of Tan-Lu fault zone in the Early Mesozoic. Kendong fault, Changdi fault, and Gudong fault which fault strike is NNE are arranged in echelon to the right row from north to south, reflecting the right-lateral strike-slip character of Tan-Lu fault zone in the Late Mesozoic. The stress system converted from left-lateral strike-slip to right-lateral strike-slip during the Mesozoic. The changes of stress in different

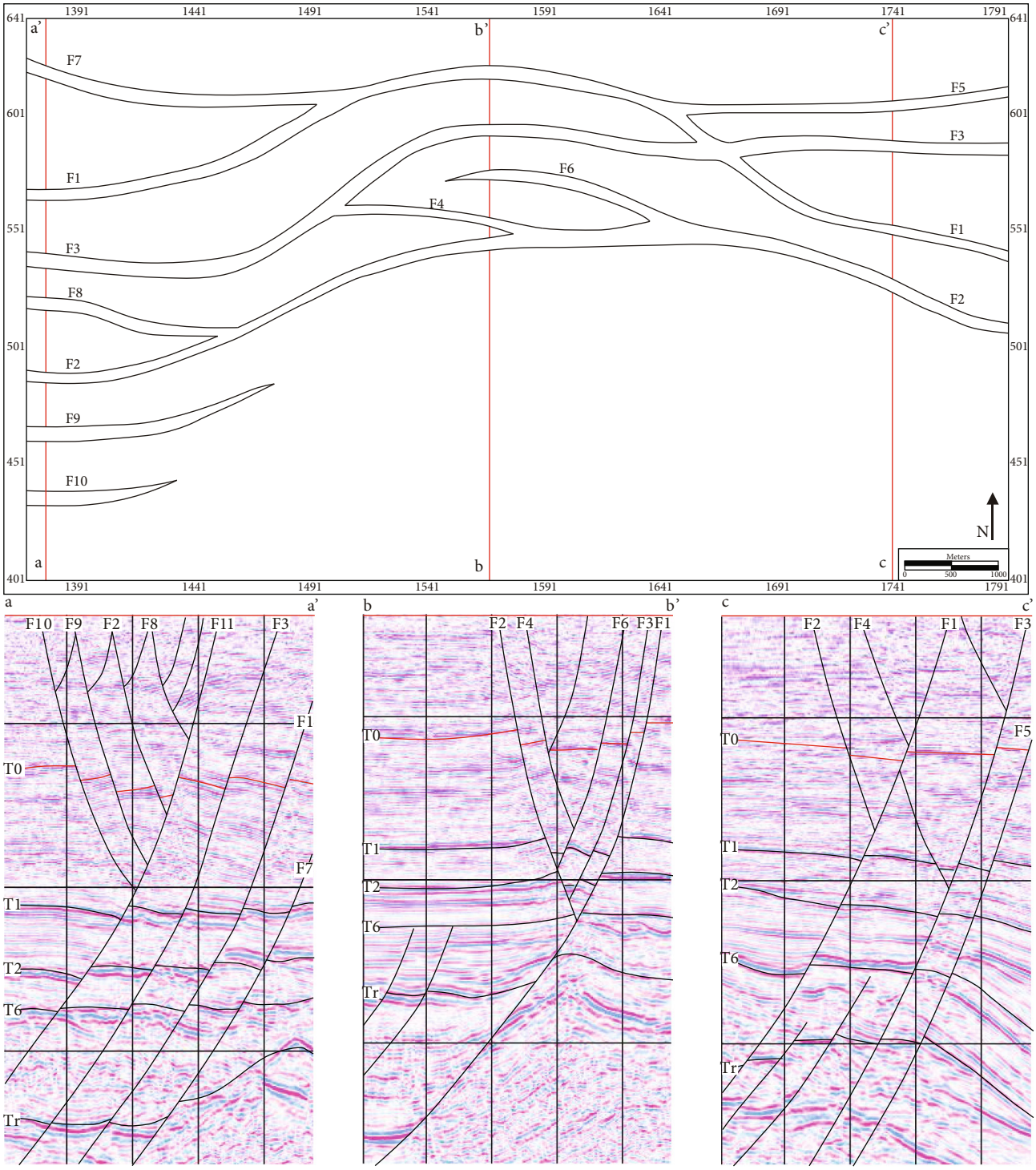


Figure 10: Fault combination styles in plain and section of T0 reflection horizon.

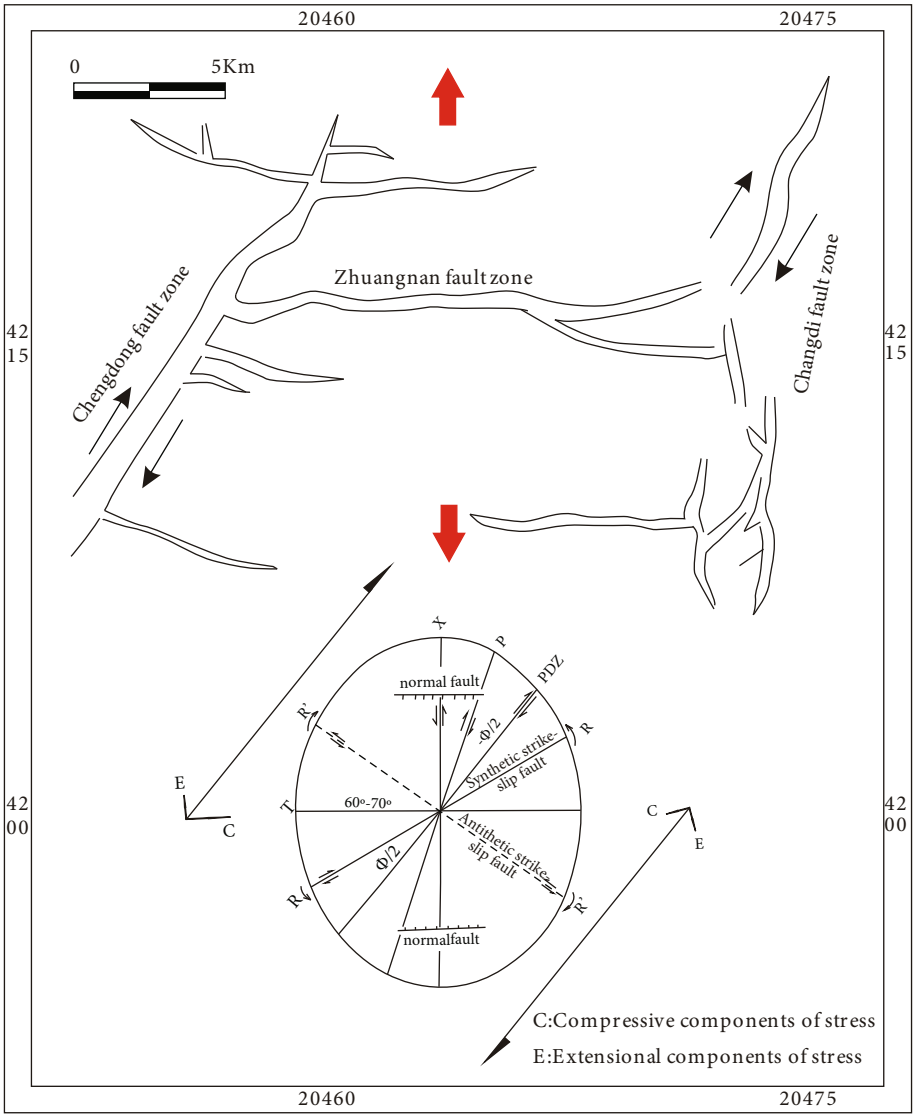


Figure 11: Tectonic stress field of Zhuangnan fault zone.

geologic periods created complex superimposed structures and form the present fracture systems in Zhuangnan fault zone.

## 5. Geological Evolution and Dynamics of Zhuangnan Fault Zone

Based on the analysis of the tectonic evolution and regional dynamic background, the geological evolution and dynamics of Zhuangnan fault zone in Zhanhua sag need further discussion and clarification.

The geometry characteristics of Zhuangnan fault zone were systematically investigated, and the results indicated that Zhuangnan fault zone has three-piece planar characterization (eastern part, middle part, and western part). The structural feature of the eastern part and western part is more complex than the middle part.

The east and west parts of the Zhuangnan fault zone are affected by different faults, and their activity is different. The faults in the middle part are the difference of fracture activity intensity between the two ends of the balance; bending deformation occurs, forming a special adjustment structure. The special arched and curved structure of the Zhuangnan fault zone reflects the process of the stress gradually transferring to the interior in the eastern and western sections.

First, it is aimed at the definitude inheritance relationship of faults in Zhuangnan fault zone by analyzing and calculating the activity of main faults developed in the eastern part and the western part.

West Zhuangnan fault zone reached Chengdong fault which fault strike is NNE. Data from moving velocity of both faults show that the activity of Zhuangnan fault was consistent with Chengdong fault.

There were two peak-activity periods of the two faults. They were the sedimentary period of the third member of Shahejie Formation and the sedimentary period of the first member of Shahejie Formation. The first peak-activity period of Zhuangnan fault zone was a bit later than Chengdong fault. The second peak-activity period of the two faults is quite satisfactory.

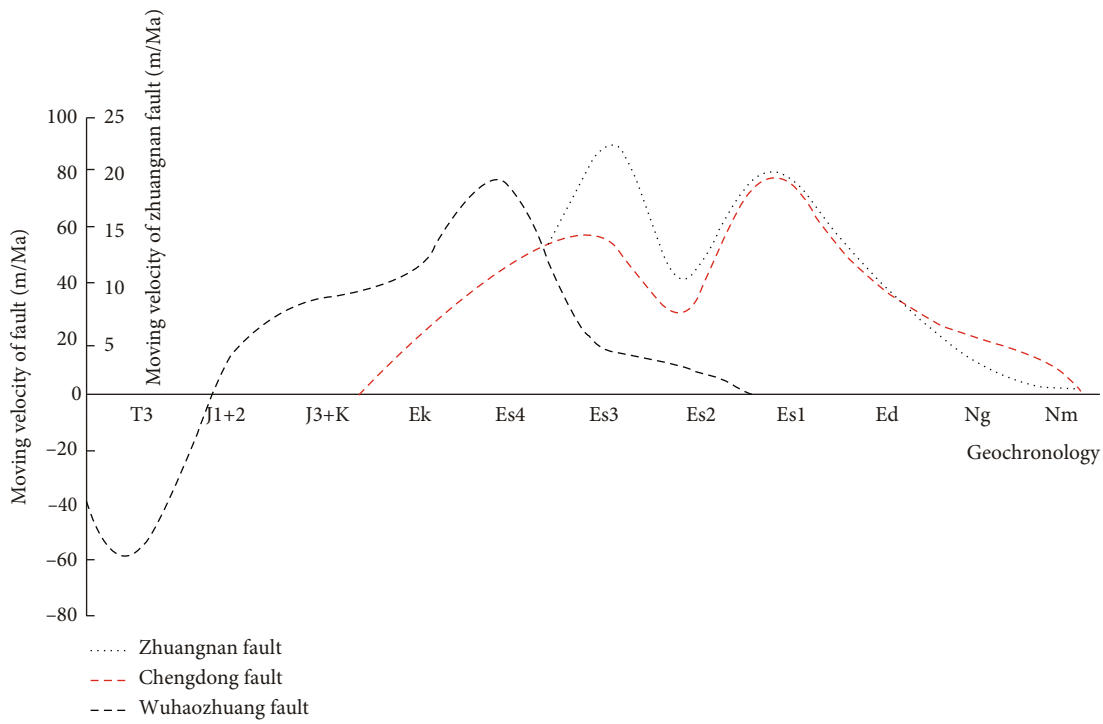


Figure 12: Activity of Zhuangnan fault, Chengnan fault, and Wuhaozhuang fault.

The active time of Chengdong fault is longer than that of Zhuangnan fault since the Late Cretaceous Period to the sedimentary period of Minghuazhen Formation. The active time of Zhuangnan fault is since the middle sedimentary period of the fourth member of Shahejie Formation to the sedimentary period of Minghuazhen Formation. When the active time of Chengdong fault reaches the first peak, Zhuangnan fault has started to develop.

From the sedimentary period of the third member of Shahejie Formation, the moving velocity of both faults is quite satisfactory. These indicate that the activity of Chengdong fault is the most important direct factor in the activity of West Zhuangnan fault zone. Meanwhile, Zhuangnan fault plays a great role in the reconstruction of Chengdong fault.

East Zhuangnan fault zone reached two faults, Changdi fault which fault strike is NNE and Wuhaozhuang fault which fault strike is NW, respectively.

The activity of the two main eastern boundary faults of Zhuangnan fault zone is Changdi fault and Wuhaozhuang fault. The Changdi fault and Wuhaozhuang fault strike nearly south-north. Changdi fault is a representative strike-slip fault zone in the east of Jiyang Depression, which included deep and shallow fault systems. The deep fault system is the main body of Changdi fault. The shallow fault system consisted of NS-trending left-order en echelon faults (Figure 12).

Branching faults developed in the east wall of Changdi fault, which showed the "入" Chinese character form shape combined with the main fault, which was caused by the difference of boundary conditions during horizontal twisting. The eastern part of Zhuangnan fault zone connects with the west side of Changti fault, and the west side of Changti fault develops a fault terrace, which cuts with the east-west strike faults. The Zhuangnan fault developed gradually from east to middle, which is accompanied by intense fault activity. Zhuangnan fault zone as the main east-west strike-slip accommodation structure plays an important regulating role. Therefore, the activity of the Changdi fault plays an important role in controlling the structural development of the Zhuangnan fault zone

The activity characteristics of Wuhaozhuang fault who has long-term activity controls the development of the tectonic framework of Zhuangnan fault zone. From the fourth member of Shahejie Formation to the third member of Shahejie Formation, the activity of Zhuangnan fault was really just started and gradually increased. However, activities of Wuhaozhuang fault have come to the last stage, and large-scale fault activities stop. The structure activity of East Zhuangnan fault zone has been less affected by Wuhaozhuang fault (Figure 4).

Our knowledge of the fault properties of Changdi fault has some disagreements among the experts. At present, the unified understanding of Changdi fault reached is primarily the regional structure evolution. Changdi fault is located in the west Tanlu strike-slip fault zone. Affected and controlled by the strike-slip fault zone, faults are developed. The formation of Changdi fault experienced a complex evolutionary process. Changdi fault is still prominently featured in the characters of strike-slip and extrusion structure despite being reconstructed by NS extension in Cenozoic. The eastern segment of Changdi fault exhibits a complex structure composed of several branches, shaping the "入" Chinese character form fault array with Changdi fault. Structures differ greatly in features between the two sides of Changdi fault.

The western segment of Changdi fault was cut into a series of complex fault noses and fault blocks which fractures are faulted steps on the section by faults of EW fault strike. The differences in trend and margin condition are the main reasons for the different actions in structural belts. Zhuangnan fault zone plays a vital role in balancing the differences of margin condition as the main E-W strike-slip accommodation structure. In turn, Changdi fault makes important effects on the fault evolution of East Zhuangnan fault zone.

## 6. Conclusions

This paper focuses on the structural formation, evolution, and genetic mechanisms of Zhuangnan fault zone in controlling hydrocarbon migration of unconventional rocks. From three aspects of geometry, kinematics, and dynamics in conclusion, below is a summary of what we learned through this study.

(1) Zhuangnan fault zone has two functions as the main E-W strike-slip accommodation structure. That is, on the one hand, Zhuangnan fault zone inherited the rules of development of regional tectonic. On the other hand, the present structure framework of Zhanhua sag was reconstructed by Zhuangnan fault zone

(2) In geometry, the cross-sectional fracture forms of the Zhuangnan fault zone are mainly shovel type (Zhuangnan main fault) and plate type, generating four types of combination—"y" type combination, compound "y" type combination, stepped combination, and horst combination. The plane fracture forms include arched bending (Zhuangnan main fault), straight, curved, and "S" curved. The plane combination styles mainly include feather row, horsetail, grid, diagonal, and parallel

(3) Zhuangnan fault zone has a three-stage distribution structure on the plane: the eastern and western sections have a large number of faults, and the spreading range is large; the middle section has a small number of faults, and the development position is concentrated. The structure characteristic of the east and west parts of Zhuangnan fault zone is more complex than the structure characteristic of the middle part of Zhuangnan fault zone

(4) Based on the plane and section structural styles of Zhuangnan fault zone and the analysis of dynamic evolution, it is found that Zhuangnan fault zone has a law of inheritance development and evolution between deep and shallow fault systems. In space, it has the bottom-up characteristics of complex-simple-complex evolution

(5) Through the tectonic evolution and dynamic research of regional and Zhuangnan fault zone, it was found that Zhuangnan fault zone is manipulated by the activity of the three main boundary faults of Zhanhua sag (Changdi fault, Wuhaozhuang fault, and Chengdong fault). The offsets of the three boundary faults gradually decrease into the accommodation zone, so the tectonic framework of Middle Zhuangnan fault zone has been less affected by boundary faults. Zhuangnan fault is the only fault in dipping S which cut the overlying formations and basement strata. The arch bending in the middle part of Zhuangnan fault zone is to balance the significant differences between the activity intensity of the two main boundary faults of Zhanhua sag

## Data Availability

There is no data to support the findings of this study.

## Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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