1. Introduction

The Gaoliu structural belt is geographically located in Tanghai County, Tangshan City, Hebei Province, and structurally located in Nanpu Sag. A lot of previous studies have been done on the genetic mechanism of the Gaoliu structural belt. Zhou Tianwei believes that the evolution of the fault system in Nanpu Sag is controlled by the Cenozoic south-north extension mechanism [1]. Cai Rui think tall willow fault zone was formed in 165 under the action of tensile stress of stretching structure [2], the tall willow tectonic belt formation mechanism on predecessors’ understanding of basic consistent, but for the joint of the high north and willow fault, due to its close to big fault, poor seismic data quality, high in the north fault down dish of fallen faults are divided the understanding of the formation and evolution, tectonic interpretation reliability is low, affect oilfield development for a long time To solve this problem, this paper carries out structural physical simulation experiment of typical deep section of Gaoliu structural belt, reproduces the history of structural deformation and evolution, and analyzes the superposition and transformation relationship between fault systems in different periods, in order to provide a basis for oilfield development.

2. Regional overview

Nanpu Sag, where Gaoliu structural belt is located, is located in the north end of Huanghua depression in Bohai Bay Basin, adjacent to the East-West Yanshan uplift fold belt in the North China platform. It
is a typical continental fault basin dustpan depression developed by Mesozoic and Cenozoic fault block activities on the basement of North China platform, with the structure of North fault, South fault, East fault and west fault [3, 4]. The northern boundary faults of Nanpu Sag are Xinanzhuang fault and Bogezhuang fault, which are in the shape of "human" on the plane and control the northern boundary of the sag [5, 6] (Fig. 1). The southern boundary fault is Shabei fault, which forms the southern boundary of the depression. The secondary controlling faults are Nanpu fault, Gaoliu fault and Hetuo fault, which are active faults in the depression for a long time.

Gaoliu structural belt belongs to the secondary structural deformation zone of Nanpu Sag, sandwiched between the nearly EW trending Gaoliu fault and the Gaobei fault. Several nearly EW trending normal faults are developed on the north side of Gaoliu structural belt, which are distributed in parallel belts and combs. The East and west sides intersect with Bogezhuang fault and Xinanzhuang fault. The formation of the Gaoliu structural belt is mainly related to the evolution of the NE trending Xinanzhuang structural belt and the NW trending Bogezhuang structural belt.

The Xinanzhuang and Bogezhuang faults are the main faults controlling the tectonic evolution of the study area. It is mainly characterized by syngenetic faults and post sedimentary faults, and mainly by tensile normal faults with the characteristics of torsional sliding [7]. Among them, Xinanzhuang fault is dextral and Bogezhuang fault is sinistral. The Xinanzhuang and Bogezhuang faults were formed in Mesozoic era, the active period was in Cenozoic Paleogene, and the fault activity was not strong in Neogene [8].

Fig. 1 Tectonic location map of Nanpu sag

3. Fault characteristics of Gaoliu structural belt

3.1. Fracture plane distribution characteristics
The deep interior of Gaoliu structural belt is cut into several small fault blocks by faults, and the whole strata incline southeast and gradually uplift northwest. There are many NE trending normal faults in the north of the fault, which mainly incline to NW and distribute in parallel belts. The East and west sides of the fault intersect with Bogezhuang fault and Xinanzhuang fault. In the middle part, there are many nearly EW and NE normal faults, which are distributed in a zigzag oblique fault zone. In the south, there are several nearly NW and NE trending normal faults, which are distributed in a brush like oblique fault zone (Fig. 2).

3.2. Fault profile characteristics
The characteristics of Gaoshangbao deep fault in seismic profile are composed of Gaobei fault and Gaoliu fault, which are inclined in the same direction and the secondary faults developed in the hanging wall. The occurrence of Xinanzhuang, Bogezhuang, Gaobei and Gaoliu faults are characterized by a shovel shape with steep top and gentle bottom, while other faults are mostly planar faults [9]. The reverse faults developed close to the Bogezhuang boundary fault and the main boundary faults form a "Y-shaped" combination (Fig. 3). The quality of shallow seismic data is relatively good, mainly developing
small-scale normal faults, which tend to be opposite to the main faults, and some secondary faults and main faults are combined into "flower shape" on the section, which indicates that the late tectonic activity in the study area has both extensional and strike slip properties [10].

![Fig. 2 Plane tectonic model of Gaoliu structural belt](image)

Note: Black represents going near NEE and Tendency to south east. Blue represents near NEE and Tendency to north west. Green represents the near NW direction and Tendency to north east. AA 'represents the location of the seismic section line in Figure 4.

![Fig. 3 Typical section structural model of Gaoliu structural belt](image)

4. Physical simulation experiment

4.1. Model design
The structural physics simulation experiment is based on the similarity theory [11] to study the deformation characteristics and evolution process of the model. In order to verify the deformation process and genetic mechanism of Gaoliu structural belt, based on the in-depth analysis of its deformation characteristics, the typical seismic interpretation section (Fig. 4) in the study area is selected as the geological model for physical simulation analysis. According to the principle of gradual approximation, the experiment gradually achieves the similarity with the seismic interpretation model by changing the main factors affecting the deformation, such as the basement model and the extension rate.
4.2. Model device
One side of the fixed end of the experimental model is made up of polystyrene plastic blocks to form a shovel boundary. The main boundary fault of Bogezhuang in the study area is simulated. Along the shovel boundary fault, non-retractable canvas and rubber are laid at the bottom of the model, which are connected with the movable baffle at the other end. The baffle can be stretched by a motor (Fig. 4). The loose quartz sand, which is widely used in the study of brittle deformation, is selected as the experimental material with the particle size of 40-60 mesh.

4.3. Experimental conditions
The experiment was carried out in three stages: first, laying five layers of PZ, MZ, Es32 + 3, Es31 and Es1. After the experiment, the motor started the first stage of tension (V1 = 2 mm/min). After a series of normal faults in the same direction and reverse direction appeared in the hanging wall of Bogezhuang fault, the extension stopped, and the stratum after the first stage of tension was paved (simulating synsedimentary phenomenon). Then, laying ed well and entering the second stage of tension (V2 = 2 mm/min)) When two faults with the same direction (representing Gaobei fault and Gaoliu fault respectively, cutting the previous reverse fault) and their associated secondary faults develop in front of Bogezhuang fault, the motor stops and the second stage of tension ends; after the extended strata are paved, the last two layers of ng and nm are laid, and then the third stage of tension begins (V3 = 2 mm/min), when a series of secondary normal faults with the same direction and reverse direction developed on the upper part of Bogezhuang fault, Gaobei fault and Gaoliu fault, the tension stopped and the experiment ended. The experimental temperature was 20 ℃ and the interval of taking pictures was 2 minutes.

4.4. Experimental results
A total of 33 groups of profile simulation experiments have been completed. This paper focuses on the analysis of five representative groups of experiments (Table 1).

Experiment 1 was a rigid base without uplift, in the first stage, when the extension reaches 4.6cm, the extension stops when the reverse fault is formed. In the second stage, when the extension reaches 6.6cm, the same direction fault begins to form. At the same time, the rolling anticline is formed at the boundary of the shovel fault. With the increase of the extension, the bending amplitude of the rolling anticline gradually increases, but there is no new fault on the profile.

Experiment 2 is a single uplift experiment on rigid basement, at the bottom of the model, a fixed position foam plate (long 10cm, high 0.8cm) is preset to simulate the underlying uplift. In the first stage, the extension reaches 5.1cm and stops when two reverse faults with similar attitude are formed on the hanging wall of the boundary fault. After laying ed, the extension is continued, and the second stage extension reaches 8.2cm, and the extension stops when two faults are formed in the same direction. After laying ng and nm, continue to stretch, when the stretching amount reaches 12cm, the "cabbage" style is formed on the profile, and stop stretching.
Fig. 5 Sketch map of experimental device

Table 1. Basic parameters of experiment

| Experiment name | Basement type        | Basement uplift         | Stretching distance/cm | Drawing speed / (mm/min) |
|-----------------|----------------------|-------------------------|------------------------|--------------------------|
| Experiment 1    | Rigid (canvas)       | No basement uplift      | 14.6                   | 1                        |
| Experiment 2    | Rigid (canvas)       | Single basement uplift  | 12                     | 2                        |
| Experiment 3    | Rigid (canvas)       | Double basement uplift  | 13.2                   | 2                        |
| Experiment 4    | Toughness (rubber)   | No basement uplift      | 20                     | 2                        |
| Experiment 5    | Toughness (rubber)   | Double basement uplift  | 9                      | 2                        |

Experiment 3 was a double uplift experiment on a rigid base. In the middle of the model, two foam plates were placed under the cotton cloth to simulate the uplift of the substrate. In the first stage, the extension amount reaches 3.6 cm, which stops when the same direction fault is formed, and continues after laying ed. In the second stage, the extension amount reaches 6.4 cm, which stops when the reverse fault is formed near the boundary fault. After laying ng and nm, continue to stretch, and stop stretching when the stretching reaches 13.2 cm.

Experiment 4 was the experiment of ductile basement without hump, a stretch rubber is laid on the bottom of the model, and the angle between the rubber and the baffle is 15 ° at the movable end. When the movable end begins to stretch, the rubber can move synchronously with the baffle to transfer the stress to the overlying sand layer. When the first stage of extension reaches 10.4 cm, a fault with the same dip direction is formed in the hanging wall of the shovel type boundary fault, and then a series of faults with similar occurrence and reverse dip with the main boundary fault are developed successively. The second stage of extension begins after the Ed is laid. When the extension reaches 13.6 cm, two faults incline in the same direction as the main boundary fault are formed. The first reverse fault is cut off, and the third stage of extension is started after the tension is stopped and ng and nm are laid. When the extension reaches 20.0 cm, another fault in the same direction is formed. Most of the first faults develop upward and cut to the top, and the fault shape gradually evolves from the original plane fault to the top it's a shovel fault with steep and gentle dip.

Experiment 5 is a ductile basement double uplift experiment, a telescopic rubber is laid on the bottom of the model, and both ends are fixed on the baffles on both sides. On the top of the rubber, two foam plates are fixed to simulate the underlying uplift. When the active end starts to stretch, the rubber and foam board can synchronize with the baffle to transmit stress to the overlying sand layer. When the extension reaches 4.8 cm, the reverse fault and the same direction fault are formed between the basement uplift and the active baffle. When the extension reaches 9.0 cm, the whole section forms a "Horst graben" combination pattern around the two basement uplifts.
5. Analysis of experimental results

The above five groups of experiments have simulated the deformation process of Gaoliu structural belt from the aspects of basement conditions, synsedimentary conditions and extension direction, and the experimental results are different in different degrees.

The canvas at the bottom of the model can only transfer the extensional displacement, but it does not extend and deform, representing the basement with strong rigidity. The simulation results of Experiment 1 have some similarities with the actual geological section (Fig. 6). Some reverse faults are developed in the similar position of the hanging wall of the boundary fault, but the deformation is mainly limited near the Bogeju fault, which is equivalent to the structure of the ascending wall of the Gaobei fault. But in Experiment 1, no fault corresponding to Gaobei and Gaoliu was found.

![Fig. 6 No uplift experimental simulation results of rigid base](image)

Experiment 2 and 3 set up the basement uplift (simulated by thin foam board) on the basis of the experimental 1 model, and studied the influence of the pre-existing basement uplift on the deformation of the cap rock. In Experiment 2, a foam board was fixed at the bottom of the model. After the experiment, two positive and two faults were formed at the two ends of the foam board to form a graben. The deformation continued to concentrate on the foam board when it continued to expand, and formed two near faults corresponding to the high North and high Willows (Fig. 7). The descending disk is further deformed.

![Fig. 7 Simulation results of single uplift test on rigid base](image)

The model of double basement uplift was used in Experiment 3. Similar to experiment 2, the initial deformation occurred near the basement uplift (Fig. 8), forming faults roughly corresponding to Gaobei and Gaoliu. Then, the stress was mainly concentrated between the boundary fault and the adjacent basement uplift, and the strain was mainly limited to the ascending wall of Gaobei fault (and mainly formed faults in the same direction similar to the occurrence of Gaobei fault). In the downthrow of Gaobei and Gaoliu faults, there is still no deformation corresponding to the geological section.

![Fig. 8 Simulation results of double uplift experiment on rigid basement](image)

The results of Experiment 1, 2 and 3 show that the "V" shaped combination, "Y" shaped combination and "comb" shaped combination similar to the seismic interpretation model can be formed near the
boundary fault. However, under the condition of rigid basement, no matter setting the pre-existing uplift of basement or changing the extension rate, it can not form a result similar to the geological section in the study area.

Therefore, the model of ductile substrate was used in Experiment 4 and 5, and rubber was chosen as the medium of displacement transfer. During the stretching process, the rubber not only transfers the stretching displacement to the upper overburden, but also simulates the effect of the stretching of the ductile base with weak rigidity on the deformation of the overburden. The simulation results of Experiment 4 are more similar to the seismic profile interpretation model in the study area. In the case of basement extension deformation, a series of secondary faults can be developed in the hanging wall of the boundary fault in reverse (Fig. 9). When the detachment surface is buried deeply and extended enough, not only secondary faults can be formed in reverse with the main boundary fault, but also a series of secondary faults can be formed when the extension continues The syn fault with similar attitude cuts off the previous reverse fault.

![Fig. 9 No uplift experimental simulation results of ductile basement](image)

In Experiment 5, two pre-existing uplifts were set in the basement, and the deformation was mainly concentrated near the basement uplift or limited between the two uplifts (Fig. 10).

![Fig. 10 Simulation results of double uplift experiment on ductile basement](image)

In general, the deformation characteristics of experiment 1-3 and experiment 4-5 are similar to those of the actual section. The simulation results of experiment 1-3 are highly similar to those of the actual section in the shape of the reverse fault which is equivalent to the ascending wall of the Gaobei fault (Fig. 4 and Fig.6). However, no matter how the above experimental conditions are changed, it is impossible to form the opposite fault with Gaobei and Gaoliu under the condition of no basement pre-existing uplift Even if the basement uplift is set up and the faults corresponding to Gaobei and Gaoliu are formed, the hanging wall of the fault can no longer develop the deformation similar to the actual section.

In contrast, the deformation results of Experiment 4 have higher similarity with the actual section (Fig. 4 and Fig.9). The main features are as follows: ① In the hanging wall of the boundary fault, the reverse fault is formed, which is similar to the actual section, and is mainly developed before Ed deposition. ② Gaobei fault and Gaoliu fault developed during Ed deposition period, which cut the former reverse fault into two parts. ③The Gaobei and Gaoliu faults controlled the deposition of Ed, and the Gaoliu fault had a large amount of activity during the Ng and Nm periods.

Through the analysis of the above simulation experimental results, we can get the following enlightenment: the simulation study of rigid basement model shows that the structural deformation corresponding to the ascending wall of Bogezhuang fault can be realized; the experimental results of
ductile basement model show that the deformation style of Gaoliu structural belt is related to the base extension, and the experimental results are consistent with the actual section in terms of final shape and deformation period. The results of surface interpretation are similar. Therefore, it can be considered that the Gaoliu structural belt was formed in the late stage of basement extension.

6. Conclusion
The normal faults, which strike NE and dip NNW, are controlled by the Bogezhuang and Xinanzhuang faults and formed in the early stage of extension. Gaobei fault and Gaoliu fault are normal faults formed in the late stage of extension, which are in the same direction with the main boundary faults such as Bogezhuang fault and Xinanzhuang fault. They cut the early reverse normal faults and control the deposition of strata after Dongying Formation in varying degrees.

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