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Study on the Formation Mechanism of The Strike-slip Fracture Zone in the Gulongnan Area of the Songliao Basin

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Abstract: The Gulongnan strike-slip fracture zone consists of multi-phase active faults, which play a crucial role in the transportation of hydrocarbons generated from depressions to the slope area, and is of high research value. However, the main controlling factors of reservoir formation in the context of the development of strike- slip fracture are still unclear, and the success rate of drilling wells is low, so there is an urgent need to carry out the research work on the formation process of strike-slip fracture zones and the mechanism of genesis. Based on the principle of similarity, this paper investigates the tectonic style and evolution law of extension and extrusion under the control of strike-slip faults in the study area through tectonophysical simulation experiments, in order to reproduce the dynamical evolution process, and achieves a high degree of agreement with the actual geological situation. The experimental results show that at the end of the depositional stage of the Qingshankou Formation in the study area, a weak east-west extrusion formed the dorsal tectonics, and then a strong east-west stretching formed the strike-slip fault zone, and the tectonic pattern of the study area was controlled by the two main faults formed in the early stage of the extrusion.

Keywords: Gulongnan area; Songliao Basin; sandbox tectonic physical simulation experiment; strike-slip fracture.

1. Introduction

Fracture system is an important element in the formation of oil and gas basins, which has multiple control effects on the formation of enclosures and the formation of oil and gas deposits. A number of large oil and gas fields of "strike-slip fracture control type" have been discovered both at home and abroad, such as the oil and gas-bearing basins in the Southern California area under the control of the San Andreas strike-slip fracture zone in the United States. Recently, many exploratory wells deployed along the strike-slip fracture zones in the Tarim Basin have obtained high oil and gas production (Lu Xinbin et al. 2015; Qiu Huabiao et al. 2017; Jiao Fangzheng 2018; Wang Yuwei 2019), which has made the study of the multi-stage strike-slip fracture-controlled reservoirs in the Harahatang, Yueman, Shunbei, and Shunnan areas a hot spot. Highly productive oil and gas wells are closely related to fractures, so it is urgent to find lithologic trap and high-quality oil layers in the Gulongnan area of the Songliao Basin, where there are multi-stage strike-slip fractures.

On the basis of fine tectonic interpretation, it is imperative to select favorable tectonic enclosures and carry out research on the formation process and genesis mechanism of the strike-slip fracture zone in the Gulongnan area. After more than one hundred years of rapid development, the sandbox tectonic physical simulation experiment, with its basic features of high degree of similarity, detailed experimental process, and clear experimental results, has been widely noticed and applied in the academic world and the field of petroleum exploration. Through the geometric analysis of the original seismic data and the design of the experimental model and parameters, the deformation of the geologic body is simulated by means of the orthotropic method, so as to achieve the purpose of reconstructing the mechanical model of tectonic evolution.

Based on the high-precision 2D seismic data and tectonophysical simulation experiments in the Gulongnan area of the Songliao Basin, this paper analyzes the tectonic characteristics of the strike-slip rupture in the study area and its formation and evolution process in the study area, and discusses the mechanism of strike-slip rupture in the Gulongnan area.

2. Regional Geological Background

2.1. Stratigraphic characteristics

The Songliao Basin is a large-scale Meso-Cenozoic terrestrial basin in northeastern China, and the study area is located in the Central Depression Zone, a primary tectonic unit in the northern part of the Songliao Basin, geographically located in Zhaoyuan County, Daqing City, Heilongjiang Province. Tectonically, it is located at the southern end of the Qijia-Gulong Depression in the Central Depression Area, which is a faulted depression basin (Fig. 1), developed in the Late Jurassic and Cretaceous, and was formed by the mantle thermal energy and stratigraphic pressure provided by the plate extrusion movement. The stratigraphy of the study area consists of bedrock, Yingcheng Formation (K1 y), Dengloukou Formation (K1 d), Quantou Formation (K1 q), and Late Cretaceous Qingshankou Formation (K2 qn), Yaojia Formation (K2 y),Nenjiang Formation (K2 n), Sifangtai Formation (K2 s), Mingshui Formation (K2 m), and the Cenozoic stratigraphy in the order of the bottom to the top.

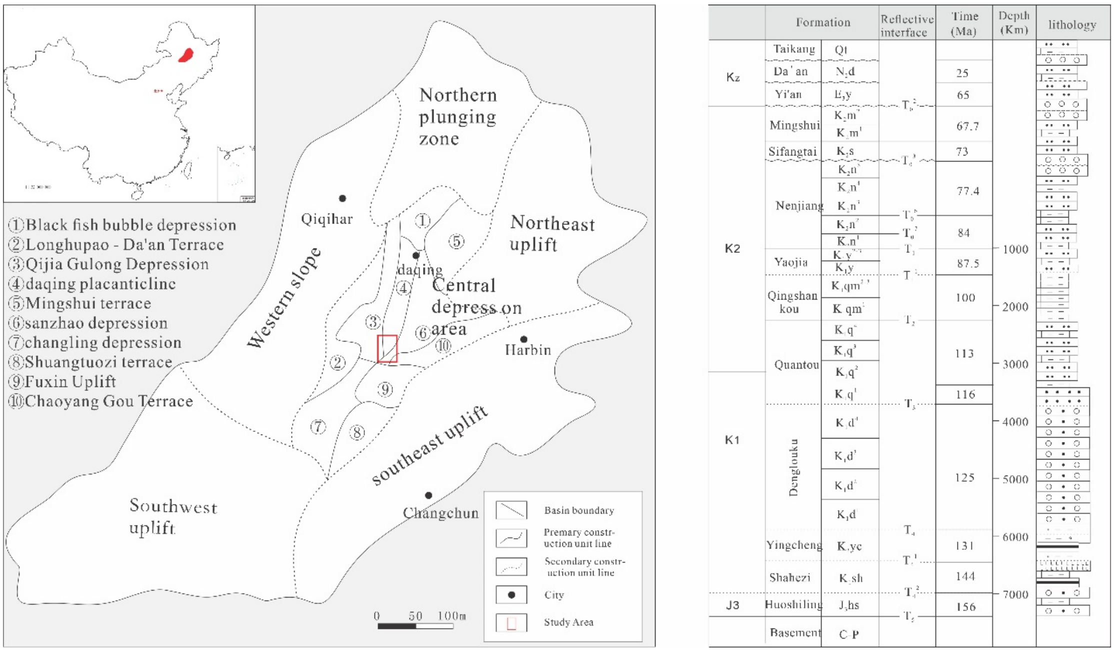

Figure 1. Comprehensive histogram of tectonic position and stratigraphy of the study area

2.2. Structural characteristics of fault profiles

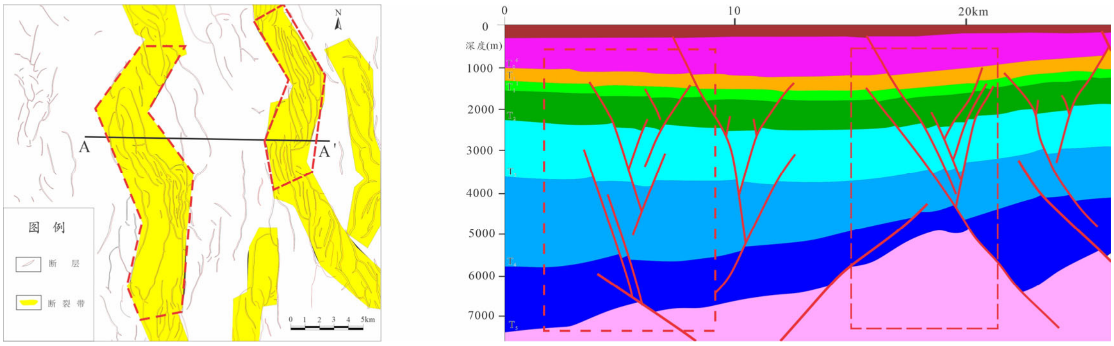

Figure 2. Seismic plan A-A'

In the section over the study area (Fig. 2), we can see that the main faults are two deep and large faults cutting the basement, and with the age of the stratum becoming newer, the fracture spacing has a tendency to become smaller, which is in line with the fracture spacing development law of the same sedimentary faults. The secondary faults are distributed along the two main faults, and the tendency is opposite to that of the main faults, with a smaller scale, and they are not developed in the locations where no basal faults are developed, and most of them only cut one or two layers, which are obviously controlled by the basal faults, and the whole faults are in a multi-stage "Y"- shaped combination in the section.

In the study area, the formation of a dense zone of strike-slip fractures developed at the end of the Qing section of sedimentation is divided into two stages. (i) the formation of micro-amplitude broad and slow backslope under the weak extrusion in the near east-west direction in the early stage; and (ii) the formation of north-north-east oriented right-trending right-step strike-slip fracture zones under the strong tensile force in the near east-west direction in the late stage, which is controlled by the pre-existing basal fractures that are diagonally intersected by the tensile force. The influencing factors will be further verified by experiments next.

3. Tectonic Physics Simulation Experiment

Tectonophysical simulation experiments were firstly proposed by the famous geologist Hall (1815) in the early nineteenth century, mainly used to simulate the deformation and dislocation of rocks in nature, which created a new idea, a new method and a new means in the field of tectonophysical geology research. On the basis of the basic principle of experimental similarity, sandbox physical simulation uses appropriate mechanical equipment and materials to enlarge or reduce the prototype year-on-year (Li Zhongquan, 2010), which is the most intuitive means of reproducing the process of geologic evolution in the natural environment and revealing the mechanism of its tectonic dynamics (Long Wei, 2017), and it has a strong superiority in the geometrical analysis of the complex underground geologic structures, thus it has attracted a lot of attention. It has attracted extensive attention in academia and petroleum exploration, and has been widely used in the actual research process.

Based on the geometrical characteristics of the strike-slip faults, the present study analyzes the boundary conditions of the experiment, combines the theory of fault- related folding, and analyzes the tectonic styles of folds and faults, and designs the experiment according to the overall tectonic characteristics of the Gulongnan strike- slip faults, and then conducts tectonophysical simulation experiments in the Tectonics and Mineralogy and Deposits Laboratory of the Ministry of Natural Resources, Chengdu Polytechnic University.

3.1. Experimental materials

Materials commonly used in tectophysical simulation experiments include dry quartz sand, silica gel, glass beads, clay, petroleum jelly, talcum powder, and so on. In the natural gravity field environment, the deformation of loose and dry quartz sand follows the Moore-Cullen rupture criterion, which is very close to the brittle deformation behavior of sedimentary rocks in the shallow part of the earth's crust (10,000-15,000 m) (W-P Schellrt, 2000), which is an ideal material for simulating brittle rock formations in the upper crust.

This experiment is mainly aimed at the systematic study of the tectonic style of the Gulongnan strike-slip fault, so loose and dry quartz sand is selected as the preferred experimental material, the average density of the quartz sand selected in the experiment is 1297 kg/m^3 , the particle size is between 0.3 and 0.4 mm, the rupture internal friction angle is about 31°, the cohesion is 923 Pa, and the coefficient of internal friction is about 0.55 (Long W., 2018).). In order to facilitate the observation of the experimental process as well as the deformation and dislocation of the model and the characteristics,quartz sand with different colors but the same mechanical properties was selected to simulate different strata for the experiments.

3.2. Experimental setup

This experiment uses the device of the comprehensive experimental platform for tectonic deformation physics simulation in the State Key Laboratory of Tectonogenesis and Mineralization and Depository of Chengdu University of Science and Technology.

The sand box consists of transparent glass panels with fixed height and width, and the force source is provided by the electric cylinders on both sides of the baffle plate. A piece of plastic cloth is placed at the bottom of the sand box, and the plastic cloth is tightly fastened to fix the model, and then the model is fixed on the right movable baffle plate, so that the movable baffle plate can drive the model to move. During the experiment, quartz sand was laid between the substrate and the right baffle to simulate the brittle stratum.

A piece of polystyrene foam substrate is placed at the bottom of the sand box to simulate the pre-existing substrate. The length of the lower boundary of the substrate is 170 mm, the length of the upper boundary is 120 mm, the width is 300 mm, and the height is 45 mm. the size of the sand box is 43 cm × 30 cm × 9 cm. based on the designed model, white quartz sand is laid at the bottom of the sand box flush with the substrate, with the thickness of about 45 mm, and then a layer of thin green marking layer, and the overlaying ground layer is laid with three layers of 1-cm white quartz sand, and each layer is covered with a layer of marking layer. Each layer is overlaid with a marker layer. The right movable baffle was fixed, and the left movable baffle could be extended and extruded under the force of the left driving cylinder, and the extension and extrusion speeds were set to 0.4mm/s (Figure 3).

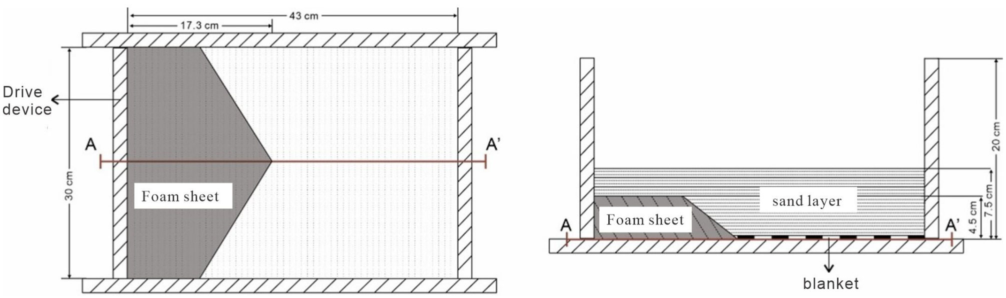

Figure 3. Schematic diagram of the experimental apparatus

The data recording in the experiment was done by staged measurements of the experimental process in addition to the traditional photographic recording, a method that allowed the surface to be properly contoured and visualized, encompassing all the major and many minor faults at the same time as responding to the degree of undulation in the surface elevation. At the end of the experiment, an appropriate amount of water was added to soak the sand body, and the internal structural features of the experiment were observed and measured by cross-cutting.

3.3. Model setup

The key to the success of a physics simulation experiment is the similarity between the model and the prototype. The degree of similarity between the experimental model and the prototype is an important criterion for the success or failure of simulation experiments (Chuanxiang, War, 2010; Shijun, Zhao, 2010).Hubbert (1937) proposed that three similarity criteria (geometric, kinematic, and kinetic) can ensure that the model is scaled appropriately. Considering that the basement boundary is closely related to the morphology of the basin and the characteristics of its internal fracture system, and based on the results of previous studies on the basement, which show that the basement fault blocks in the area are "V" shaped, and that the spreading direction of this pre-existing structure located in the west is in the NW direction, the foam plate of the similarity model was polished (4.5 cm in height and 43° in angle), and was placed on the left side of the experimental setup (Fig. 4).

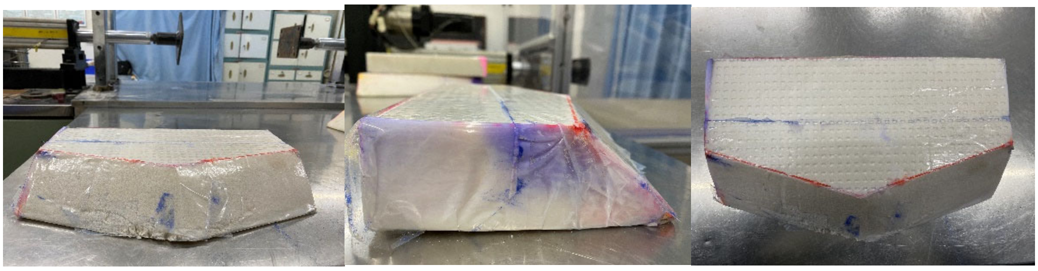

Figure 4. Morphology of foam boards simulating preexisting substrate fracture

4. Experimental Procedure and Results

4.1. Experimental process

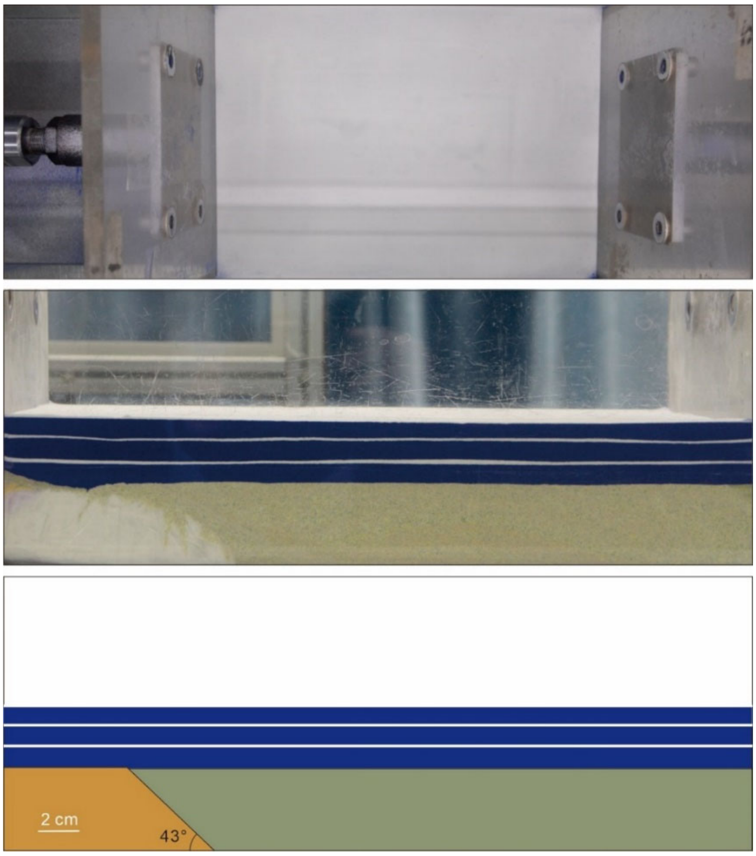

Figure 5. Initial stage of the physical simulation experiment

The initial shape of the experiment is shown in Fig. 5. The initial stress of the experiment is unilateral extrusion, and then it transitions to unilateral tension. At 22 mm of unilateral extrusion, the extruded reverse fault located at the boundary of the tectonically weak zone is the first to develop, and the location and distribution direction of the backslope development are controlled by the boundary fractures. In plan, the location near the basement fault block is slightly uplifted, albeit with a small amplitude, and the development of extrusion reverse faults on both sides can be observed. The longitudinal section shows that the fractures propagate from the boundary of the tectonic zone to the center of the tectonic zone, but the cutting of the central bulge is not obvious. As the amount of extrusion increases, the dorsal tectonics narrows, the faults develop further, and the central bulge in the plunge zone is still uncut, and the style of the tectonic zone does not change (Fig. 6).

After the end of extrusion, the tensile stage is entered, and the left side is tensioned by 40 mm with a tensile velocity of 0.04 mm/s. The experimental simulation results show the elevation changes in the cross section of the model boundary. The correspondence between flat and longitudinal sections is very obvious, two groups of extruding reverse faults are developed at the boundary of the tectonic zone, two groups of tensile positive faults are developed inwardly, and the development of secondary depressions is obvious. During the stretching process, it is found that with the gradual increase of the stretching amount, the stress gradually spreads to the center of the tectonic belt, and a new set of tensile normal faults gradually develops between the two extruding reverse faults, and these two new faults develop in the center of the tectonic belt, and the fracture spacing of the early-developed faults increases further, and the depressions further become deeper and wider. The tectonic zone as a whole is characterized by a "graben-base-graben" pattern (Figure 7).

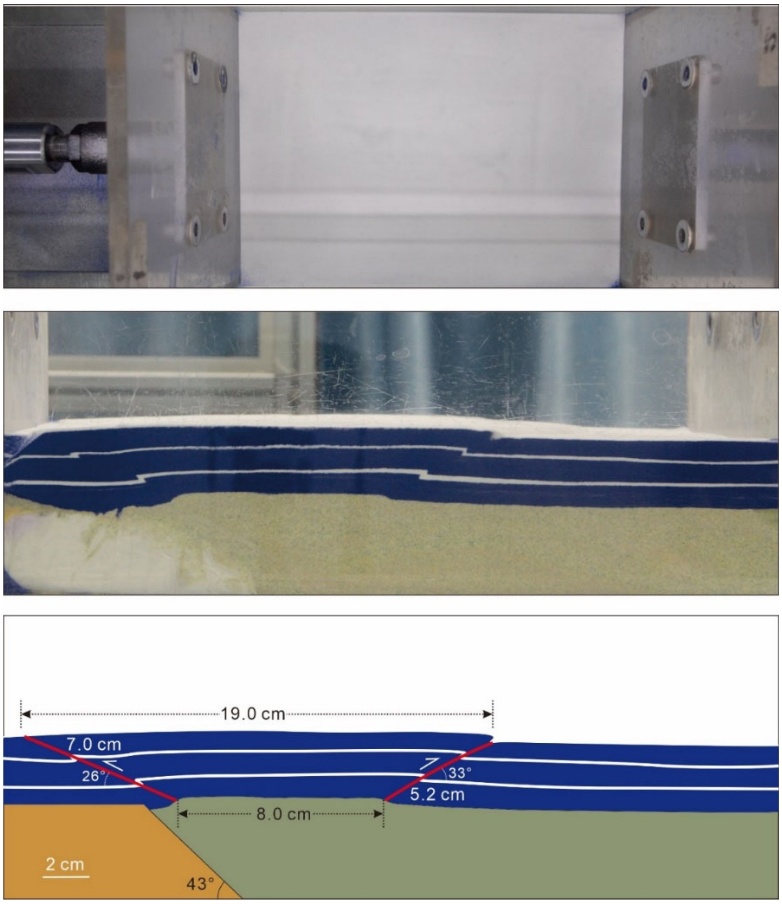

Figure 6. Extrusion phase of the physical simulation experiment

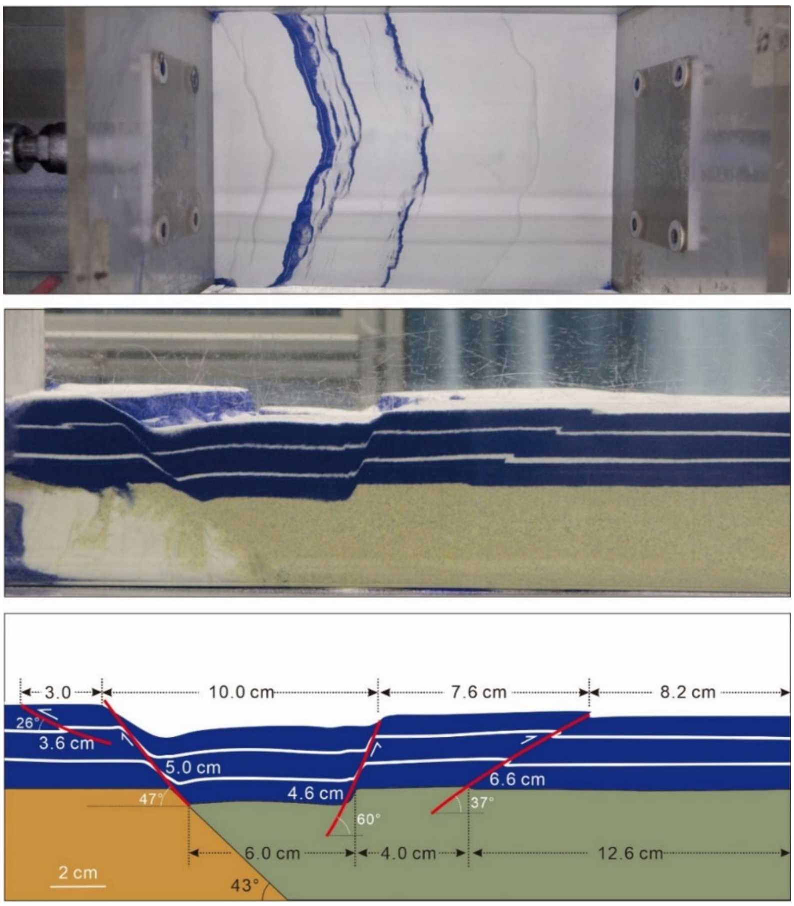

Figure 7. Stretching phase of the physical simulation experiment

The differential distribution of faults is characterized more clearly after cutting (Fig. 8). It was found that, in addition to the two main-stem extruded reverse faults and two main-stem tensile normal faults observed previously, three secondary tensile normal faults were developed between the main-stem normal faults, and these minor faults were formed at the latest time. This phenomenon can also be observed in plan, where they form three secondary minor fault traps. Vertically, the fracture breaks in the vertical zone away from the base of the fault block are all small but numerous. Towards the sides, the fracture spacing gradually increases and the number decreases, reflecting the continuity of the evolution of the secondary depressions controlled by the boundary fault block.

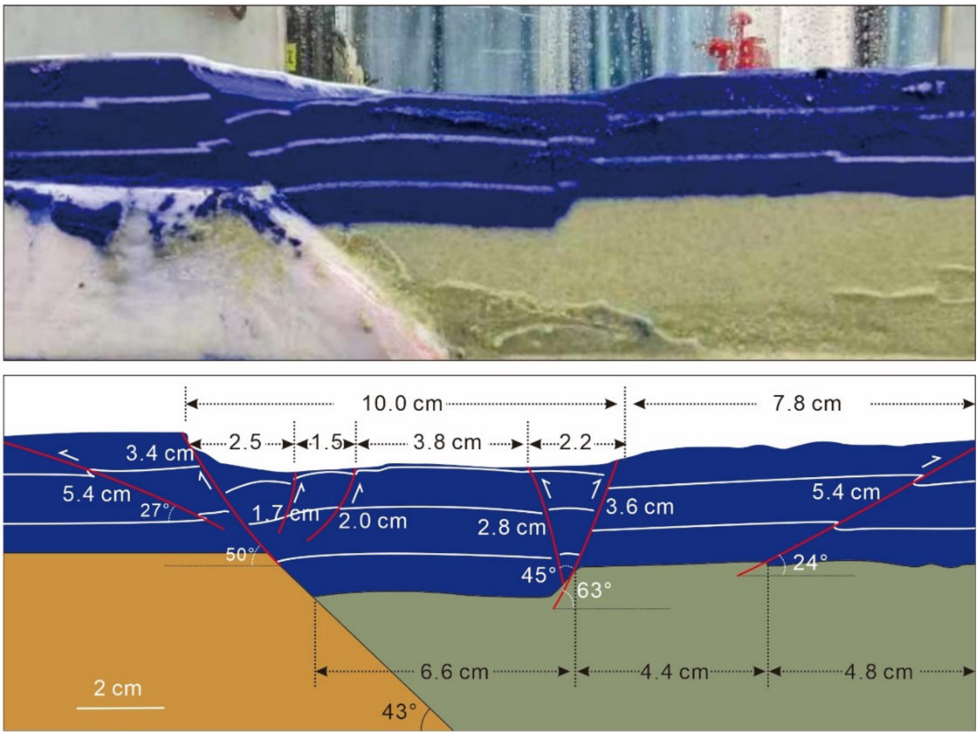

Figure 8. Physics simulation experiment cutting stage

4.2. Evolutionary sequences

This tectonic experiment is divided into two stages, extrusion and tension, and the sequence of the formation of each fault is shown in Figure 9.

squeeze-out phase

Fault No. ①: two reverse faults controlled by the basal faults, first developed at the two ends of the sandbox.

elongation stage

Fault No. ②: close to the basement fault block, belongs to the companion fault of fault No. ①, and was initially formed during the stretching phase.

Fault No. ③: close to the basement fault block, it belongs to the companion fault of Fault No. ②, and is concentrated in the plane at the tip of the fault block, and gradually disappears to both sides. Therefore, it is not fully visible in the uncut section. Fault No. ④: a position between two faults No. ①, which is earlier than fault No.

③ in the profile, but later than fault No. ③ in the plane.

Fault No. 5: It was formed at the latest time and is a companion fault of fault No.

4.3. Experimental results

Tectonophysical simulation experiment is to simulate the tectonic development of the study area based on regional dynamics in the laboratory environment, so as to reproduce the tectonic deformation process in nature and study the mechanism of its tectonic genesis. By conducting physical simulation experiments on planar and sectional sections of the fracture zones in the region, the formation pattern of the fracture zones and the activity of secondary faults are investigated, so as to further analyze the genesis mechanism of the fracture zones.

Throughout the tectonic simulation experiment, the two main faults formed by the early extrusion tectonics controlled the evolution of the whole tectonic style.

Afterwards, due to the influence of regional extensional forces and pre-existing faults, the faults are more active, and a large number of small multi-directional faults are developed between the large faults, among which the small faults above the pre-existing faults are the most developed, forming a dense zone of faults. A small number ofthese small faults are directly connected with the pre-existing faults, but the cutting depth is shallow, forming a "Y"-shaped tectonic pattern. In the final stage of stretching, the stretching intensity becomes smaller, the activity of the faults decreases, some of the faults in the previous stage are activated and continue to develop upward, and at the same time, smaller faults of a more subordinate level are also newly formed, which constitutes the present pattern of the fracture zone.

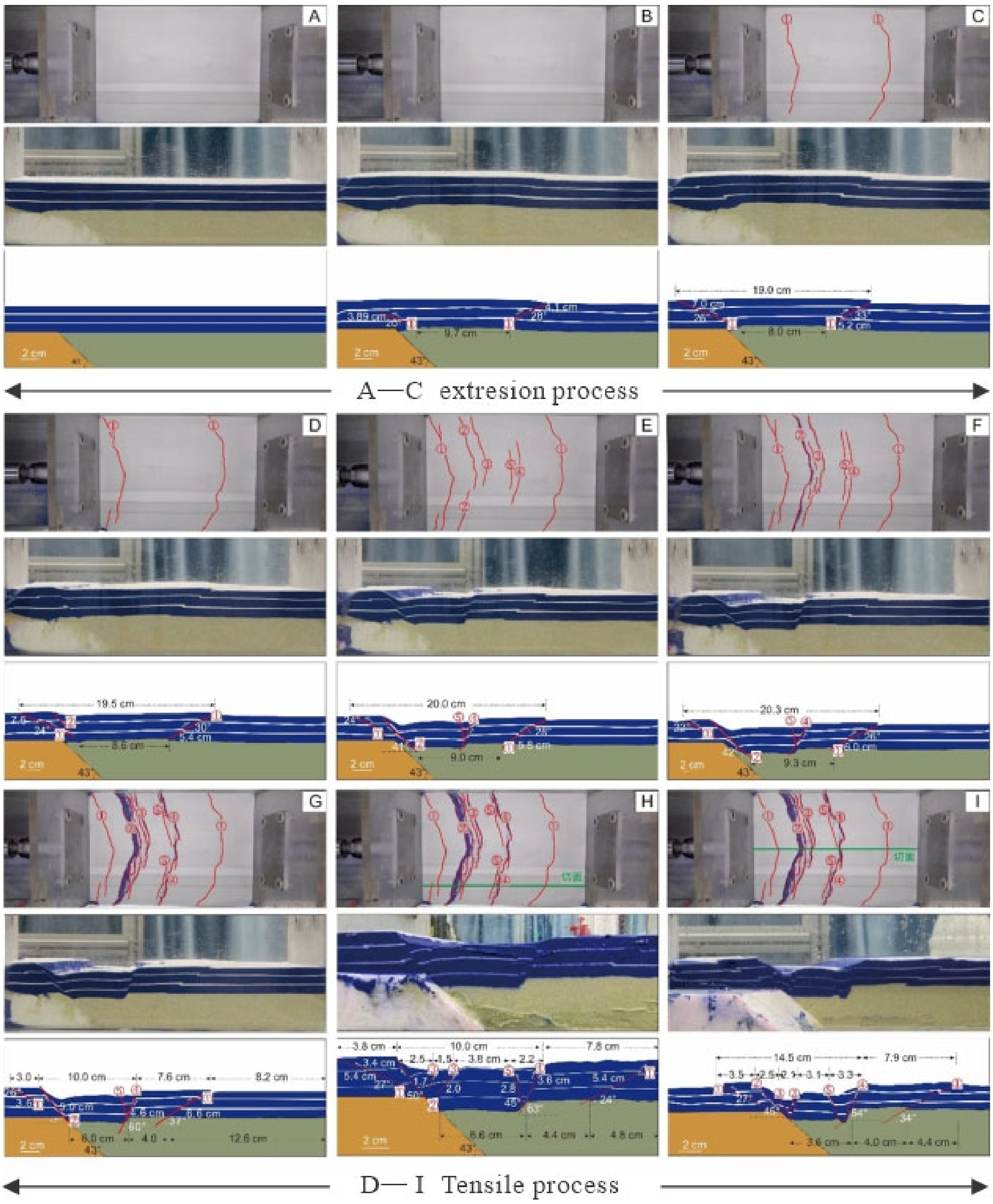

Figure 9. Complete evolutionary sequence of extrusion-stretching

5. Conclusion

(1) At the end of the deposition of a section of the Qingshankou Formation, it first underwent a weak east-west extrusion and then changed to a strong east-west stretching, which formed a dorsal tectonic structure, and a strike-slip fault zone was formed by a strong east-west stretching.

(2) The tectonophysical simulation of the strike-slip fault profile in the Gulongnan area reveals that, in the simulation, the two main faults formed by the early extrusion tectonics control the evolution of the entire tectonic style, and a large number of multi- directional small faults are developed between the large faults under the influence of the regional extensional force, and a small number of these small faults are connected to the pre-existing faults directly to form a "Y-shaped" tectonic style. "The Y-shaped tectonic pattern is formed by the direct connection of a few of these small faults with the pre-existing faults.

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