Tectonic characteristics and favourable exploration regions of Guaizihu Sag in Yin'e Basin

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Abstract: The exploration degree of Guaizihu Sag is low. In recent years, the drilling in this area has shown good oil-gas properties and revealed a huge exploration prospect. Based on the regional tectonic background and drilling, logging and seismic data, we clarified the structural characteristics and basin structure in different period. The results show that the extending direction of the sag is NNE, and it is a half-graben rift with down faulting at the eastern boundary and overlapping at the western boundary. The sag is composed of rift strata and depression strata, and has gone through 3 stages of structural evolution: faulted stage, fault-depressed transitional stage and depression stage. The tectonic activity of boundary faults have a weak-strong-weak trend. In the early faulted stage, there are many half-graben existing together. Then the basin gradually evolves into a typical half-graben basin in late faulted stage. The landform becomes more gentle in depression stage. The favorable exploration regions are in the slope zone and steep slope zone, where the sand body is near the source rock and has a good fault connectivity.

1. Introduction
Basin tectonic evolution is controlled by regional geological background, basement property, etc. [1-2]. Only a few scholars have studied the tectonic evolution of Guaizihu Sag. Chen et al. [3] hold that the Guaizihu Sag has similar characteristics to the Yin'e Basin in terms of tectonic evolution. Jin et al. think that the sag is composed of rift strata and depression strata, and has gone through 3 stages of structural evolution [4].

Guaizihu Sag is a new block with low exploration degree. Although the successful drilling in recent years has revealed a good prospect of oil and gas resources, the complex tectonic background and evolutionary characteristics of the basin are still unclear. Based on high-accuracy 3d seismic interpretation, drilling and logging data and regional geological background, this paper explains the cretaceous tectonic evolution characteristics of the sag and predicts the favorable exploration regions. The results not only provide geological basis for the study of sedimentation and reservoir in this area, but also provide ideas for the development of near source exploration in the sag.

2. Regional geological setting
Yin'e Basin is located in the western part of Inner Mongolia Autonomous Region of China. It is tectonically located in the structural junction of Tarim, Kazakhstan, Siberia and North China plates(Fig.1).

Yin'e Basin is a rift strata and depression strata superimposed Meso-Cenozoic basin developed on the basis of Precambrian metamorphic crystalline basement and Paleozoic folded basement, and it
undergoes plate tectonic evolution, intraplate extension and intracontinental orogeny\textsuperscript{[5-6]}. The main body of the sag is formed in the intraplate extension stage, which is divided into north sag, middle sag and south sag, with an area of about 2600km\textsuperscript{2}. The middle sag covers an area of about 800km\textsuperscript{2} and is mostly covered by 3D seismic, it can be divided into slope zone, depression zone and steep slope zone from west to east. The north sag has not been studied because of the mining right, while the south sag is mainly measured by 2D seismic.

Guaizihu Sag is mainly composed of Cretaceous and Cenozoic, among which the Cretaceous is divided into Bayingebi Formation, Suhongtu Formation, Yingen Formation and Wulansuhai Formation. Bayingebi Formation can be divided into Ba-1 member and Ba-2 member, and the Suhongtu Formation can be divided into Su-1 member and Su-2 member\textsuperscript{[5-8]}. Ba-1 member is the main hydrocarbon-generating strata, and the source rocks have reached hydrocarbon-generating threshold. Multiple sets of source-reservoir-cap assemblages are developed in the sag from the bottom up. The good reservoirs are mainly distributed in Bayingebi Formation and upper part of Su-2 member, and the favorable structural belts adjacent to source rocks have good exploration prospects.

3. Structural features

The sag is divided into basement, rift strata and depression strata from bottom up. The middle sag and the south sag are composed of steep slope belt, depression belt and slope belt. The main distribution direction of the structural belt in middle sag is NE, while the direction of the structural belt in south sag is NNE(Fig.1).

In the course of evolution, Guaizihu Sag has been influenced by many tectonic movements and formed a complex fault system. Main faults control the boundary, axial direction, sedimentation center and tectonic division of the basin, such as F1, etc. Secondary synsedimentary faults affect sedimentary filling, such as F2, F4, etc. (Fig. 2).

In early cretaceous, the whole area was affected by tensile force and pull-apart force, and formed many synsedimentary faults. At the end of the early cretaceous, there was a large amount of magma gushing and a large subsidence of the lithosphere. At this time, the basin was transformed from a rifting and pull-apart basin into a depression\textsuperscript{[6]}. Thus, it can be divided into three stages: faulted stage, transitional stage and depression stage.
The faulted stage includes Bayingebi and Su-1 period. In this stage, the fault throw is large, the extension distance is long, and there are many faults. The intensity of fault activity experienced a process from slight to severe and then to slow down, which resulted in various basin frameworks and paleogeomorphologic features. The transitional stage includes Su-2 and Yingen period, during which fault activity is greatly reduced. Except for F1, other faults activities basically stopped in the middle sag, and other faults of the south sag were still in small-scale activities. The depression stage is from Wulansuhai period to quaternary, and the gradual cooling of mantle material slowed down the fault activity in Yin'e area. Under the influence of regional compensation\cite{9}, it became a stable thermal subsidence depression.

4. Tectonic evolution

4.1 Activities of main synsedimentary faults

The growth index, fault throw and fault activity rate of synsedimentary faults can be used to quantitatively characterize fault activity\cite{10-12}. In this paper, throw and activity rate of 6 typical faults were analysed (Fig.2). The activity of boundary faults began in Ba-1 and Ba-2 period with a small rate of activity. The activity in the Su-1 period was the most intense, and it was greatly reduced in Su-2 period. Then, it tended to stop in the sedimentary stage of Yingen Formation. However, the activity of secondary synsedimentary faults reached the maximum in Ba-1 period, and then gradually decreased. After Su-2 period, most of those faults disappeared in the middle sag, and just several faults in the south sag remained weak.

![Fig 2. Activities of main synsedimentary faults in Guaizihu Sag](image)

4.2 Tectonic evolution and control factors

On the basis of previous studies on the tectonic evolution of continental faulted basins and the tectonic characteristics of Yin'e Basin\cite{2-9,13-14}, combined with the active stage and stratigraphic distribution of Guaizihu Sag, the tectonic evolution process was analysed by means of balanced section method (Fig.3).

The basin was controlled by tension-torsional stress in Ba-1 period, and the boundary fault activity intensity was relatively large. The lake controlled by boundary fault became deeper and the basin range expanded. A set of mudstone of shallow and semi-deep lake deposited, forming a set of important source rocks in the sag. Secondary synsedimentary fault activity was the strongest during this period and controlled several subsags. The geomorphic feature of the basin was "multiple semi-grabens co-existing", and the internal deposition thickness of each subsag was large (Fig.3-a).
In Ba-2 period, all the faults activities were weakened, and the paleogeomorphology of "multiple semi-grabens co-existing" became gentle. The edge of the sag suffered uplift and denudation at the end of the Ba-2 period (Fig.3-b).

The main faults activities were the strongest and the secondary faults activities were still weakened in Su-1 period. The depression region was significantly thickened, the lake reached the maximum depth and range, and transgression happened again. Although the quality of the source rocks formed in this period is far worse than that of the source rocks in the Ba-1 member, the mudstone can be used as a good regional cap. Uplift and denudation can be seen at the edge of the basin at the end of the Su-1 period, forming a relatively large regional unconformity (Fig.3-c).

Fig 3. Tectonic evolution profile in Guaizihu Sag

The intensity of rifting activity in the Su-2 period decreased significantly, basin landform tended to be flat, and lake contracted (Fig.3-d). In the sedimentary stage of Yingen Formation, a certain thickness
of strata was deposited in the study area on the basis of low-amplitude uplift in the early stage. At the end of the Yingen period, the sag suffered compression, uplift and denudation due to the influence of 5th episode of Yan Shan orogeny (Fig.3-e). After that, the basin entered the stage of depression, where faults stopped and geomorphology was gentle, forming Wulansuhai Formation and extensive tertiary deposition (Fig.3-f, Fig.3-g).

5. Favorable exploration regions
The favorable exploration regions in Ba-1 member include the northern long-axis tilted zone, the central uplift slope zone, the eastern steep slope zone, the southern faults-transfer zone and the faults-transfer zone in the south sag (Fig.4-a). The northern long-axis tilted zone has a large structural trap area, and its south side is adjacent to high-quality source rocks. Faults and basement unconformity can be good channels for oil and gas migration. High quality sandstone reservoirs are developed in the central uplift slope zone. The downdip direction of this area is adjacent to the high quality source rocks in the eastern deep depression area. If there are sealing faults in updip direction, it is easy to gather oil and gas. The sand bodies in the eastern steep slope zone and the southern faults-transfer zone are mostly adjacent to mudstone in depression area. Although the tectonic location determines that most of the sand bodies developed here are rapidly accumulated, and the reservoir physical properties may not be good, the oil and gas show revealed by well C indicates that this area is also one of the favorable zones. The faults-transfer zone in the south sag is close to the source rocks and the fault and basement unconformity can also be used as migration channels.

The distribution of favorable regions in Ba-2 member is generally consistent with that in Ba-1 member (Fig.4-b). Although the denudation is serious in the west side of the long-axis tilted zone, well D has a good oil and gas show.

The oil-bearing siltstones and fine sandstones in Su-1 member reveal good reservoir properties, and faults connect the source rocks of Bayingebi Formation with the sand bodies in Su-1 member, the oil and gas migration conditions are good. The thick grey, livid and dolomitic mudstone developed continuously in the upper part of Su-1 member can be good cap rocks. It is speculated that favorable exploration zones are distributed in the west, northwest and north of the middle sag, while favorable zones in the south sag are still located in the faults-transfer zone (Fig.4-c).

6. Conclusion
The middle sag is a half-graben rift with down faulting at the eastern boundary and overlapping at the western boundary in cretaceous, and it is divided into slope belt, depression belt and steep slope belt from west to east. The south sag is just the opposite.

In the cretaceous, the sag is characterized by extensional structure and frequent tectonic activities, and it develops many structural styles, such as forward tilted fault terrace, reversed tilted fault terrace, forward sliding fault terrace, graben and horst.

The sag has gone through 3 stages of structural evolution: faulted stage, fault-depressed transitional stage and depression stage. The tectonic strength of the main faults experience weak-strong-weak trend and control the development of the basin. Secondary faults activities experience a process from strong to weak, and control the sedimentary filling in the basin.

Two important bases for predicting favorable exploration regions are: (1) sand bodies are close to the source rocks. (2) faults and unconformities well connect source rocks and reservoirs. The favorable exploration regions are the northern long-axis tilted zone, the central uplift slope zone, the eastern steep slope zone, the southern faults-transfer zone and the faults-transfer zone in the south sag.

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