ABSTRACT: The Chagan Depression is an important oil and gas exploration tectonic unit in the Yingen-Ejinaqi Basin, north central China. It has been revealed that the Chagan Depression has abundant oil and gas resources, but the study of hydrocarbon kitchens has not been carried out. The Early Cretaceous Bayingebi 2 Formation has the most important source rocks in the Chagan Depression. In this paper, the Bayingebi 2 Formation was selected to study the hydrocarbon kitchen evolution. The thermal maturity evolution of the source rocks and the locations and geological time of the development of hydrocarbon kitchens were revealed. The results show that the maturity of source rocks in the Bayingebi 2 Formation has reached the maximum during the middle depositional period of the Yingen Formation, and the hydrocarbon generation has ceased since the Late Cretaceous. The source rocks of the Bayingebi 2 Formation in the Chagan Depression have two hydrocarbon kitchens, namely, the western subdepression and the eastern subdepression hydrocarbon kitchens. The western subdepression hydrocarbon kitchen was formed in the Suhongtu 1 Formation depositional period and ended in the Yingen Formation depositional period. The location of the hydrocarbon kitchen was relatively stable and developed in the central and southern parts. However, the eastern subdepression hydrocarbon kitchen developed only during the Yingen Formation depositional period and was located in the north subsag of the Hantamiao sag zone. Finally, the evolution of the hydrocarbon kitchen reveals that oil and gas exploration still needs to be carried out around the western subdepression hydrocarbon kitchen and it may be considered to abandon the exploration in the eastern subdepression.

1. INTRODUCTION

The researches on hydrocarbon kitchen have guiding significance for oil and gas exploration, and the locations of hydrocarbon kitchens are vital to geological prospectors to estimate the potential volume of accumulation. The concept of hydrocarbon kitchen was first proposed by Thomas in 1985, and it was used to study the characteristics and distribution of source rock regions, including the location and distribution of hydrocarbon kitchen, the intensity of generated and expelled hydrocarbon from hydrocarbon kitchen, and the amount of generated and expelled hydrocarbon during different geological periods. There have been a lot of researches on hydrocarbon kitchen. The evolution history and hydrocarbon generation intensity of hydrocarbon kitchens is often studied by basin simulation and petroleum system analysis. El-Ghamri et al. pointed out by 1D basin models that reservoir oil in the October field originates predominantly from source rocks and the hydrocarbon expulsion was from kitchen depocenters adjacent to the October field. In the northern Bonaparte Basin, the potential hydrocarbon kitchen could be currently expelling hydrocarbons into traps on the Laminaria High according to a 3D petroleum systems model. In addition, the distribution of hydrocarbon kitchens plays an important role in oil and gas exploration. The areas near hydrocarbon kitchens may be a favorable exploration area for oil and gas, such as the Lynedoch Field and the German Central Graben. The distribution of the hydrocarbon kitchen is not only related to the quality of effective source rocks but also closely related to the tectonic–thermal history of the sedimentary basin.
carbon kitchen is essential to oil and gas exploration, and it is the basis for analyzing whether the research area has oil and gas potential. The research of hydrocarbon kitchen can provide important parameters for hydrocarbon accumulation dynamics.19−21 In China, traditionally large- and medium-scale basins with good oil and gas exploration, including the Songliao Basin and the Junggar Basin, have reached a high level of exploration and it is difficult to increase oil and gas production.22,23 To ensure the sustainable development of oil and gas production, it is urgently needed to find breakthroughs in areas with low exploration levels. The Yingen-Ejinaqi Basin covers an area of 0.4 × 10⁶ km²,24 and the Chagan Depression with greater exploration potential is the first target of resource assessment.25,26 The Chagan Depression has rich oil and gas resources and is one of the important oil production bases of the Zhongyuan Oilfield in Inner Mongolia.27 By the end of 2015, nearly 100 million tons of oil reserves had been discovered, and Jixiang and Ruyi oil fields had been established. Particularly, since October 2012, the maximum oil production of Well Yi9 in the central structural zone of the western subdepression reached 7.9 tons, which of Well X6 and Well X6-1 in the Wuliji structural zone reached 8.4 and 21.9 tons (self-blown), respectively.28 The productions further reveals that the Chagan Depression has good prospects for oil and gas exploration. Systematic evaluation of source rock characteristics has been carried out in the Chagan Depression.29−32 The results show that the source rocks are mainly developed in the Bayingebi 2 Formation, followed by the Bayingebi 1 Formation, and the Suhongtu 1 Formation is the worst. Tectonic−thermal history has been systematically studied as the basis for the study of the hydrocarbon kitchen evolution. It is considered that the Chagan Depression had the highest geothermal gradient and experienced the highest paleo-temperature during the Yingen Formation depositional period.28 The distribution and evolution of the hydrocarbon kitchen in the Chagan Depression, one of the

Figure 1. (a) Structural unit division of the Chagan Depression; (b) Structural profile; (c) Stratigraphic column. Abbreviations: JYHSB: Juyanhai subbasin; LYU: Lüyang uplift; WTHSB: Wutaohai subbasin; TLXTU: Telouxitan uplift; SHTSB: Suhongtu subbasin; DGSB: Dagu subbasin; ZNSU: Zongnasishan uplift; SHTSB: Suhetu subbasin; SDSB: Shangdan subbasin; BBTU: Benbata uplift; CGDLSSB: Chagandelesu subbasin; CLU: Chulu uplift.
important aspects in studying hydrocarbon accumulation dynamics, has not yet been carried out. Therefore, based on the development characteristics of the source rocks and the tectonic–thermal history, this paper uses basin simulation methods to restore the migration and evolution processes of the Early Cretaceous hydrocarbon kitchen in the Chagan Depression. This work may provide a basis for oil and gas exploration in the Chagan Depression.

2. GEOLOGICAL SETTINGS

The Chagan Depression has the most prospects for oil and gas exploration in the Yingen-Ejinaqi Basin, Inner Mongolia, north central China (Figure 1).27 The Yingen-Ejinaqi Basin is a Mesozoic rift basin, developed on the Precambrian crystalline block and the Paleozoic fold basement.32,33 It is bordered by the Lang Hill in the east, North Hill in the west, North Great Hill and Yabulai Hill in the south, China–Mongolia border, the Honggeerji Hill, and the Mongan Wula Hill in the north.
The Yingen-Ejinaqi Basin locates from 39° N to the China-Mongolia border, from 99° E to 108° E, and approximately 600 km from east to west and 75–225 km from north to south, with an area of about $12.3 \times 10^4$ km$^2$. The effective area of Mesozoic and Cenozoic sedimentary strata reached $10.4 \times 10^4$ km$^2$, including 8 subbasins and 5 uplifts, a total of 31 depressions, and 25 uplifts.31

The Chagan Depression is located in the central Chagandelesu Subbasin, eastern Yingen-Ejinaqi Basin. It is surrounded by the Lang Hill to the southeast, the Mubatu uplift to the southwest, and the Xi’ni uplift to the west and is separated from the Chugan uplift and the Baiyun Depression to the east. The Chagan Depression, 60 km long in the northeast and 40 km wide in the northwest, with an exploration area of about 2000 km$^2$, is a Mesozoic rift depression with a fault structure to the northwest and overlapping to the southeast.28,34 The Chagan Depression can be divided into two subdepressions and one uplift, namely, the western subdepression, the Maojiong uplift, and the eastern subdepression. The western subdepression also includes the Hule sag, Ehen sag, central structural zone, Wuliji fault-nose structural zone, and the Tulage fault steep slope zone (Figure 1a,b). The Chagan Depression has undergone three tectonic stages since the Cretaceous:24 (i) a rifting stage from the Early Cretaceous Bayingebi Formation depositional period to the Early Cretaceous Yingen Formation depositional period, during which the fault is characterized by strong activities with multiphase volcanic activity and deposition of mafic volcanic rocks and clastic rocks; (ii) a thermal subsidence stage during the Late Cretaceous Wulansuhai Formation depositional period developed in a fluvial environment; and (iii) an extrusion and uplift stage in the Cenozoic, during which squeeze thrusting occurred in locally, with the development of thrust faults and inversion structures and local deposition of the Cenozoic sediments. A total of four sets of strata developed in the Cretaceous in the Chagan Depression, which are the Early Cretaceous Bayingebi Formation (including two members), the Suhongtu Formation (including two members), the Yingen Formation, and the Late Cretaceous Wulansuhai Formation (Figure 1c).

There are three sets of source rocks in the Chagan Depression, namely, the Bayingebi 1 Formation, Bayingebi 2 Formation, and Suhongtu 1 Formation.29,35 The comprehensive evaluation of the source rocks shows that the Bayingebi 1 Formation are medium-good source rocks, which are the thickest at 450 m in the Ehen sag. The source rocks of the Suhongtu 1 Formation are evaluated as poor source rocks, which are mainly developed in the central structural zone and the Hule sag. The source rocks of the Bayingebi 2 Formation have the most potential in the Chagan Depression.29 The source rocks have reached the mature stage, and the kerogen type is mainly type II (Figure 2). The abundance of organic matter reaches the standard of medium-good source rocks. Moreover, the dark mudstone in the Bayingebi 2 Formation is
the thickest, with a maximum thickness of 1100 m in the southwestern part of the Ehen sag (Figures 3 and 4). Therefore, this study focuses on the hydrocarbon kitchen evolution in the Bayingebi 2 Formation.

3. METHODS
In this paper, the study of the hydrocarbon kitchen evolution combines the parameters during key geological periods such as the intensity and amount of generated and expelled hydrocarbon. Also, the thermal maturity evolution of the source rock is one of the essential parameters affecting the hydrocarbon kitchen evolution.\textsuperscript{36,37} According to the definitions of the hydrocarbon kitchen and studies by scholars, it can be found that focus of the research of the hydrocarbon kitchen is to determine the source rocks that provided oil and gas sources for accumulation during the geological periods. Therefore, the amount of expelled hydrocarbon of the source rocks in each sag during the geological periods can be calculated according to the maturity of source rocks, hydrocarbon generated, and expelled evolution histories. The hydrocarbon kitchen is the hydrocarbon supplying center that dominated hydrocarbon accumulation during the geological periods.\textsuperscript{1} The evolution and migration characteristics of the hydrocarbon kitchen can be determined by comparing the amount of expelled hydrocarbon (i.e., the amount of the supplied hydrocarbon) of the main hydrocarbon supplying sags (i.e., source rocks) in the Chagan Depression. Based on the analysis of drilling and stratigraphic data and related samples in recent years,\textsuperscript{14,15,25,26,28,29} this paper obtained the distribution of source rocks and geochemical characteristics distribution of source rocks in the Bayingebi 2 Formation of the Chagan Depression. Moreover, based on vitrinite reflectance and apatite fission track, this paper restored the tectonic–thermal evolution history of the study area. In addition, each stratum thickness and the amount of erosion of the key geological periods were obtained based on the seismic interpretation. All of these are the basis for the study of hydrocarbon kitchen and evolution. During the simulation, the Easy%Ro model was used to simulate the generated hydrocarbon, and the critical saturation model was used to simulate the expelled hydrocarbon.

The basic parameters include the geological parameters and geochemical parameters of the source rocks. Geological parameters include each stratum thickness, amount of erosion, thermal history, stratigraphic data, and lithological parameters. Among them, the lithological data mainly include thermal conductivity, heat production rate, rock density, compaction factor, and initial porosity. Thermal physical parameters are based on previous research results.\textsuperscript{28} Stratigraphic data is based on the actual borehole measurements. The initial porosity and compaction coefficient are obtained by regression using the method of Sclater and Christie.\textsuperscript{38} Geochemical parameters are based on existing research results, including TOC, kerogen type, and vitrinite reflectance. Present geothermal field and tectonic–thermal evolution history results are from the literature data (Figure 5).

4. RESULTS
4.1. Thermal Maturity Evolution of the Bayingebi 2 Formation Source Rocks. The evolution stages of the maturity of source rocks can be divided into five stages: immature stage (\( R_o < 0.5\% \)), low-mature stage (\( 0.5\% \leq R_o < 0.7\% \)), medium-mature stage (\( 0.7\% \leq R_o < 1.0\% \)), high-mature stage (\( 1.0\% \leq R_o < 1.3\% \)), and over-mature stage (\( R_o \geq 1.3\% \)).40 The high-mature stage is the peak stage of generated hydrocarbon, and the over-mature stage is divided into the wet gas stage (\( 1.3\% \leq R_o < 2.0\% \)) and dry gas stage (\( R_o \geq 2.0\% \)). Based on the tectonic evolution stages and tectonic–thermal
history of the sedimentary basin, this paper simulated the maturity evolution of source rocks of the Bayingebi 2 Formation at the end of the Suhongtu 1 Formation depositional period (about 107 Ma), the end of the Suhongtu 2 Formation depositional period (about 100 Ma), the middle of the Yingen Formation depositional period (about 97 Ma), and the present (0 Ma).

4.1.1. Thermal Maturity Evolution of the Top of Source Rocks of the Bayingebi 2 Formation. At the end depositional period of the Suhongtu 2 Formation, the top of the source rocks in the central and southern parts of the western subdepression of the Chagan Depression entered the hydrocarbon generation threshold and reached the medium-mature stage in Y12-Y3-Y5-Y2 well areas. However, the source rocks of the eastern subdepression have not entered the hydrocarbon generation threshold (Figure 6a). By the middle depositional period of the Yingen Formation, the source rocks of the western subdepression generally reached the medium-mature stage and reached the high-mature and over-mature stages in CC1-Y2-Y3 well areas. In contrast, the eastern subdepression had a lower maturity evolution, generally entering the hydrocarbon generation threshold in the Hantamiao sag and reaching the medium-mature stage in the depositional center of the north subsag (Figure 6b). At present, the maturity no longer increases, which is consistent with the end of the Yingen Formation depositional period (Figure 7c).

4.1.2. Thermal Maturity Evolution of the Bottom of Source Rocks of the Bayingebi 2 Formation. At the end of

Figure 7. Maturation level of the bottom of the Bayingebi 2 Formation. The contour interval is 0.1% in (a) and (b) and 0.2% in (c) and (d).
At the end of the Suhongtu 2 Formation depositional period, the bottom of source rocks generally entered the hydrocarbon generation threshold in the western subdepression and generally reached the medium-mature stage in the central and southern parts of the western subdepression. The maturity of the Y2-Y5 well areas reached the wet gas stage. Meanwhile, the Hantamiao sag zone of the eastern subdepression entered the hydrocarbon generation threshold (Figure 7b).

By the middle of the Yingen Formation depositional period, the bottom of source rocks of the western subdepression generally reached the over-mature stage in the central and southern parts and the dry gas stage in the central part. In contrast, source rocks of the eastern subdepression had lower thermal maturity evolution and generally reached the low-mature stage but only reached the medium-mature and high-mature stages in the depositional center of the north subsag of the Hantamiao sag (Figure 7c).

Subsequently, hydrocarbon generation ceased, and thermal maturity no longer increased (Figure 7d).

4.2. Generated and Expelled Hydrocarbon Evolution of Source Rocks of the Bayingebi 2 Formation. During the Suhongtu 1 Formation depositional period, the source rocks of the Bayingebi 2 Formation began generating hydrocarbon. The hydrocarbon generation center is located

Figure 8. Total amount of generated hydrocarbon of the Bayingebi 2 Formation. The contour interval is $1 \times 10^6$ t/km².
in the Yi1-Yi5-Yi2 well areas of the western subdepression of the Chagan Depression. The maximum intensity of generated hydrocarbon reached $2 \times 10^6$ t/km$^2$. At this time, the eastern subdepression had not begun to generate hydrocarbon (Figure 8a). By the Suhongtu 2 Formation depositional period, the area and intensity of generated hydrocarbon increased significantly, and the maximum intensity of generated hydrocarbon reached $11 \times 10^6$ t/km$^2$. Meanwhile, the eastern subdepression began to generate hydrocarbon, but the area and intensity of hydrocarbon generation were relatively small (Figure 8b). By the Yingen Formation depositional period, the hydrocarbon generated range increased significantly, and the hydrocarbon generation center of the western subdepression was still located in the central and southern parts (mainly in the Ehen sag). The maximum intensity of generated hydrocarbon changed little (Figure 8c). At this time, the hydrocarbon-generated range in the eastern subdepression increased greatly (Figure 8c). Generated hydrocarbon had ceased since the Wulansuhai Formation depositional period (Figure 8d).

During the Suhongtu 1 Formation depositional period, the source rocks of the Bayingebi 2 Formation did not expel hydrocarbon (Figure 9a). The expulsion of hydrocarbon did not begin until the Suhongtu 2 Formation depositional period. The hydrocarbon expulsion center was located in the southwestern of the western subdepression of the Chagan Depression, with a maximum expelled hydrocarbon intensity of

Figure 9. Total amount of expelled hydrocarbon of the Bayingebi 2 Formation. The contour interval is $1 \times 10^6$ t/km$^2$. 
4.3. Hydrocarbon Kitchen Evolution. Combining the characteristics of generated and expelled hydrocarbon during key geological periods, it is revealed that the hydrocarbon kitchen in the western subdepression of the Chagan Depression developed from the Suhongtu 1 Formation depositional period to the Yingen Formation depositional period. Since the Wulansuhai Formation depositional period, hydrocarbon expulsion has stopped (Figure 9d).

5. DISCUSSION

The hydrocarbon kitchen is the most suitable means to characterize the hydrocarbon supply center of a basin, and it is closely related to oil and gas accumulation. In this paper, generated rate, expelled rate, and the cumulative amount of hydrocarbon were used to describe the evolution of hydrocarbon kitchens. These aspects can quantitatively characterize the scale of the hydrocarbon kitchens and the evolution during the geological history stage. The results can provide a basis for large- or medium-scale oil and gas accumulation near hydrocarbon kitchens. The hydrocarbon kitchens of the Chagan Depression are mainly developed in the central and southern parts of the western subdepression and mainly during the Suhongtu 2 Formation depositional period and the Yingen Formation depositional period. Combined with basic geological characteristics such as reservoirs, traps, caps, and tectonic evolutions, we can determine the favorable areas for oil and gas accumulation. For example, the central tectonic zone of the western subdepression has good reservoir-cap combinations and is closer to the source rocks, so it is one of the favorable areas for oil and gas accumulation. Another example is the Wuliji fault-nose structural zone, which is also close to the hydrocarbon kitchen. In the depths of the Bayingebi 2 Formation, self-generated and self-stored reservoirs can be developed. The essential task is to find high-quality reservoirs. Due to the late Yanshan and Himalayan tectonic movements, the palaeo-traps were damaged and the oil and gas reservoirs were damaged and adjusted. Therefore, it is important to search for residual oil and gas reservoirs in the shallow layers (Suhongtu Formation and Yingen Formation). There is one hydrocarbon kitchen in the eastern subdepression, but the range was not sufficient to form an effective oil and gas reservoir. Therefore, there is no oil and gas display in Well H1 near the hydrocarbon kitchen.

Through the study of hydrocarbon kitchens in the Chagan Depression, it is clear that oil and gas exploration still needs to be focused on areas around the hydrocarbon kitchen in the western subdepression. Meanwhile, it may be considered to abandon the oil and gas exploration of the eastern subdepression hydrocarbon kitchen.

6. CONCLUSIONS

(1) Both the top and bottom source rocks of the Bayingebi 2 Formation of the Chagan Depression have reached the maximum thermal maturity during the Yingen Formation depositional period. Since the Wulansuhai Formation depositional period, the generated hydrocarbon has ceased.

(2) The Chagan Depression has two hydrocarbon kitchens, namely, the eastern subdepression hydrocarbon kitchen and the western subdepression hydrocarbon kitchen. The western subdepression hydrocarbon kitchen was formed during the Suhongtu 1 Formation hydrocarbon kitchen and ended during the Yingen Formation hydrocarbon kitchen. The location of the western subdepression hydrocarbon kitchen was relatively stable,
mainly developed in the central and southern parts. The eastern sub-depression hydrocarbon kitchen was developed during the Yinggen Formation hydrocarbon kitchen, and it was located in the north sub-sag of the Hantangao sag.

(3) Studies on hydrocarbon kitchen evolution in the Chagan Depression reveal that oil and gas exploration still needs to focus on areas around the western sub-depression hydrocarbon kitchen, and it is considered to give up the oil and gas exploration in the eastern sub-depression hydrocarbon kitchen.

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Notes

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