



Prediction Method of Sealing Capacity Distribution of Regional Mudstone Caprocks Damaged by Fault During the Hydrocarbon Accumulation Period

Xu Han¹, Guang Fu^{1*}, Mugui Liang¹, Fengming Jin², Guomeng Han² and Wenya Jiang²

¹School of Earth Sciences, Northeast Petroleum University, Daqing, China, ²PetroChina Dangang Oilfield Company, Tianjin, China

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*Correspondence:

Guang Fu
fuguang2008@126.com

Specialty section:

This article was submitted to
Structural Geology and Tectonics,
a section of the journal
Frontiers in Earth Science

Received: 30 March 2022

Accepted: 05 May 2022

Published: 17 June 2022

Citation:

Han X, Fu G, Liang M, Jin F, Han G and
Jiang W (2022) Prediction Method of
Sealing Capacity Distribution of
Regional Mudstone Caprocks
Damaged by Fault During the
Hydrocarbon Accumulation Period.
Front. Earth Sci. 10:908627.
doi: 10.3389/feart.2022.908627

In order to study the distribution law of oil and gas above and below the regional mudstone caprocks damaged by fault in petroliferous basins, based on the study of the sealing mechanism and degree of regional mudstone caprocks damaged by fault during the hydrocarbon accumulation period, the paleo-juxtaposition thickness of regional mudstone caprock was calculated by determining the paleo-fault throw of faults and the paleo-thickness of regional mudstone caprocks during the hydrocarbon accumulation period. According to the relation between the paleo-juxtaposition thickness of regional mudstone caprocks at known well points in the study area and the distribution of oil and gas above and below the regional mudstone caprock, the maximum juxtaposition thickness required for the upper and lower connection of the fault-associated fracture zone in the regional mudstone caprock was determined. On this basis, a set of prediction methods for the sealing capacity of regional mudstone caprocks damaged by fault during the hydrocarbon accumulation period was established. Then, this method was applied to the prediction of the damage degree distribution of the Zhangdong Fault to the regional mudstone caprock of the middle sub-member of the first member of the Shahejie Formation in the middle and late depositional periods of the Minghuazhen Formations in Qikou Sag of the Bohai Bay Basin during the hydrocarbon accumulation period. The results show that the damage degree of the Zhangdong Fault to the regional mudstone caprock of the middle sub-member of the first member of the Shahejie Formation during the hydrocarbon accumulation period is large. The largest damage appears in the east, with an a -value greater than 1, followed by the west, with an a -value between 0.5 and 1. The relatively minor damage occurs in the middle west part, with an a -value less than 0.5. The middle part is conducive to the accumulation and preservation of oil and gas generated from the source rock of the underlying third member of the Shahejie Formation, which is consistent with the fact that oil and gas discovered in the lower sub-member of the first member of the Shahejie Formation near the Zhangdong Fault are mainly distributed in its middle part. It shows that this method is feasible to predict the damage degree distribution of regional mudstone caprocks during the hydrocarbon accumulation period.

Keywords: hydrocarbon accumulation period, fault, sealing of regional mudstone caprock, prediction method, damage degree

INTRODUCTION

With the deepening of oil and gas exploration, it has been found that oil and gas are distributed above and below the regional mudstone caprocks damaged by fault, and some parts have more oil and gas than others (Gong et al., 2019; Fu et al., 2021; Zhu et al., 2021). In addition to the influence of the development of fault-associated traps and sand bodies (Zeng et al., 2021; Song et al., 2022; Zeng et al., 2022), it is mainly affected by the sealing degree distribution of regional mudstone caprocks damaged by fault during the hydrocarbon accumulation period. The greater the sealing capacity degree of regional mudstone caprock damaged by fault, the less the oil and gas under it; on the contrary, the more the oil and gas under it (Zeng et al., 2010; Zeng et al., 2013; Gong et al., 2021a; Gong et al., 2021b). This shows that accurately determining the sealing capacity degree distribution of regional mudstone caprocks damaged by fault during the hydrocarbon accumulation period is crucial for correctly understanding the distribution law of oil and gas above and below regional mudstone caprocks damaged by fault and guiding oil and gas exploration.

Some studies have been conducted on the sealing degree of regional mudstone caprocks damaged by fault, which can be summarized into the following three aspects: first, according to the relative size of fault throw and regional mudstone caprock thickness, the damage degree of fault to the distribution continuity of regional mudstone caprock has been studied (Lyu et al., 2008; Fu and Yang, 2013; Sun et al., 2013; Jiang et al., 2021). It is concluded that the larger the fault throw and the smaller the thickness of regional mudstone caprock, the greater the damage degree of fault to regional mudstone caprock; otherwise, the smaller the damage degree of fault to regional mudstone caprock (Fu et al., 2014a; Lyu et al., 2014; Fu et al., 2016). Second, based on the relative size of displacement pressure of fault rock and regional mudstone caprock, research is carried out regarding the damage degree of fault to the sealing capacity of regional mudstone caprock (Wang et al., 2017; Yu et al., 2019). It is considered that the smaller the displacement pressure of fault rock and the greater the displacement pressure of regional mudstone caprock, the greater the damage degree of fault to the sealing capacity of regional mudstone caprock; otherwise, the damage degree is smaller (Fu et al., 2014b; Fu et al., 2014c; Fu et al., 2015; Fu and Li, 2017; Zhan and Fu, 2018). Third, by combining the damage degree of fault to the distribution continuity of regional mudstone caprock and the damage degree of fault to the sealing capacity of regional mudstone caprock, the comprehensive damage degree of fault to the sealing capacity of regional mudstone caprock is investigated (Hou et al., 2015; Wang et al., 2017; Zhan et al., 2017; Jiang, 2019). It is believed that the greater the damage degree of fault to the distribution continuity and sealing capacity of regional mudstone caprock, the greater the comprehensive damage degree of fault to the sealing capacity of regional mudstone caprock; otherwise, the comprehensive damage degree of fault is smaller.

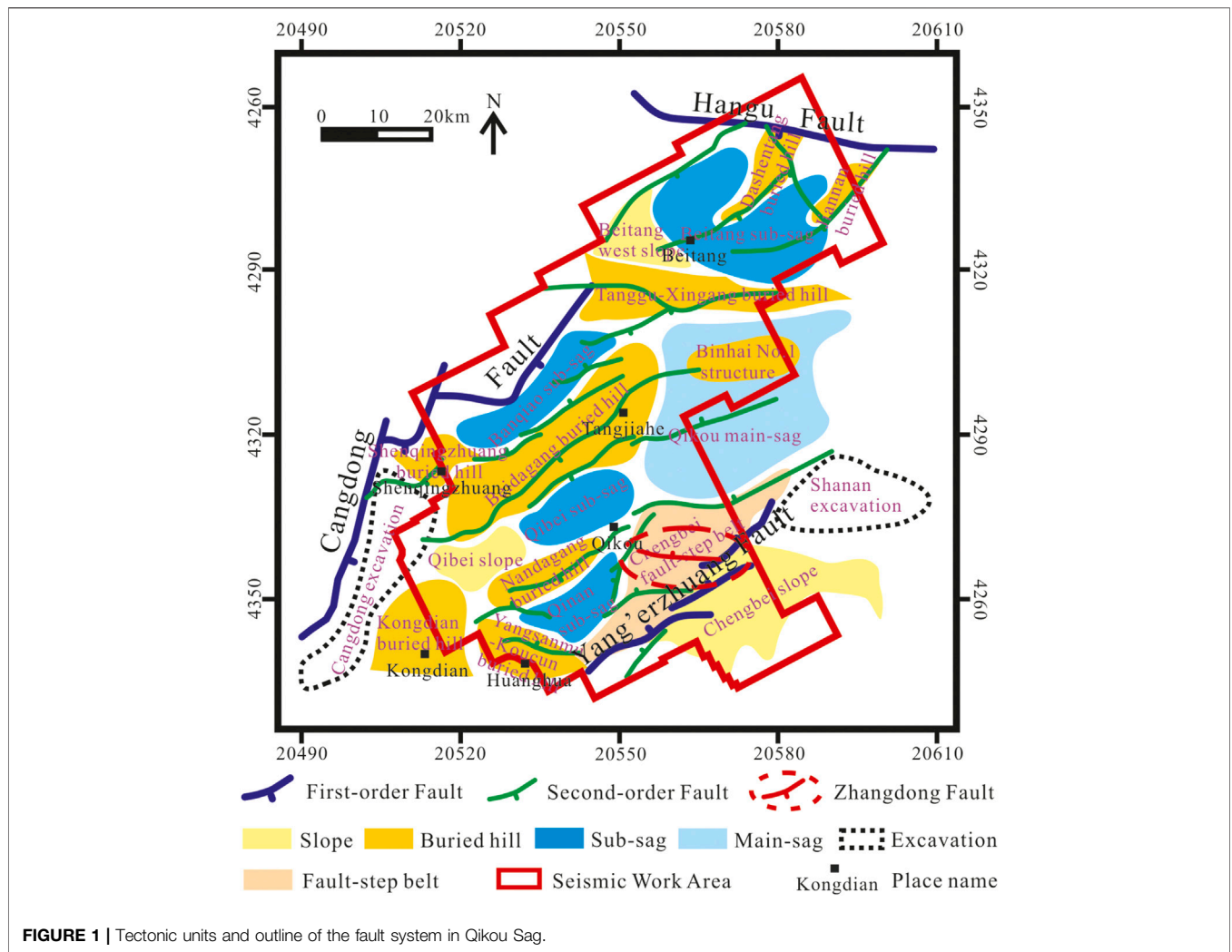
However, these studies mainly focus on the damage degree of fault to the sealing capacity of regional mudstone caprock after the fault activity stops. There are relatively few studies on the sealing

degree of regional mudstone caprocks damaged by fault during the fault activity period. It is considered that as long as the fault grows in sections in the regional mudstone caprock, which are connected up and down to become the oil and gas migration and transport channels, the oil and gas can migrate upward through the regional mudstone caprock along the fault, and the sealing capacity of the regional mudstone caprock is completely damaged by the fault (Wang et al., 2014; Fu et al., 2015; Fu and Wang, 2018; Hu et al., 2018). The damage degree of fault to the sealing capacity of regional mudstone caprock is not studied according to the relative size of the paleo-juxtaposition thickness of regional mudstone caprock, which is undoubtedly not conducive to the correct understanding of the distribution of oil and gas above and below the regional mudstone caprock. For this purpose, the research on the prediction method of the sealing degree distribution of regional mudstone caprock damaged by fault is of great significance for correctly understanding the distribution law of oil and gas above and below the regional mudstone caprock damaged by fault and guiding its oil and gas exploration.

GEOLOGICAL SETTING

The Zhangdong Fault in Qikou Sag of the Bohai Bay Basin was selected in this article. The aforementioned method was applied to predict the sealing degree distribution of regional mudstone caprock damaged by this fault in the middle sub-member of the first member of the Shahejie Formation (E_{3s1}^M) during the hydrocarbon accumulation period, and the feasibility of this method for predicting the sealing degree distribution of regional mudstone caprock damaged by the fault during the hydrocarbon accumulation period was verified by analyzing the relationship between the prediction result and the existing hydrocarbon distribution in the lower sub-member of the first member of the Shahejie Formation (E_{3s1}^L) near the Zhangdong Fault.

Located in the south of Qikou Sag, the Zhangdong Fault is a normal fault that strikes nearly east–west and extends for about 21.6 km in plane, as shown in **Figure 1**. The fault inclines to the north with a dip angle of 30–70° and breaks from the base upward to the near surface. It is a long-term inherited fault, as shown in **Figure 2**. At present, drilling near the Zhangdong Fault has revealed the Paleogene Kongdian (E_2k), Shahejie (E_{3s}), and Dongying formations (E_3d), Neogene Guantao (N_{1g}) and Minghuazhen formations (N_{2m}), and a small amount of quaternary strata (Q). The oil and gas discovered near the Zhangdong Fault are mainly distributed in the Shahejie Formation and are mostly enriched in E_{3s1}^L . The caprock is the regional mudstone caprock of E_{3s1}^L . The oil and gas mainly come from the source rock of the underlying third member of the Shahejie Formation (E_{3s3}), which belongs to the lower source rock, upper reservoir-type combination of source rock, reservoir, and caprock. The Zhangdong Fault connects the source rock of the underlying E_{3s3} and the overlying E_{3s1}^L and is active in the middle and late depositional periods of N_{2m} , so it should be the oil source fault of E_{3s1}^L . **Figure 2** shows that oil and gas discovered in E_{3s1}^L near the Zhangdong Fault are mainly distributed in its middle part, which is mainly affected by the



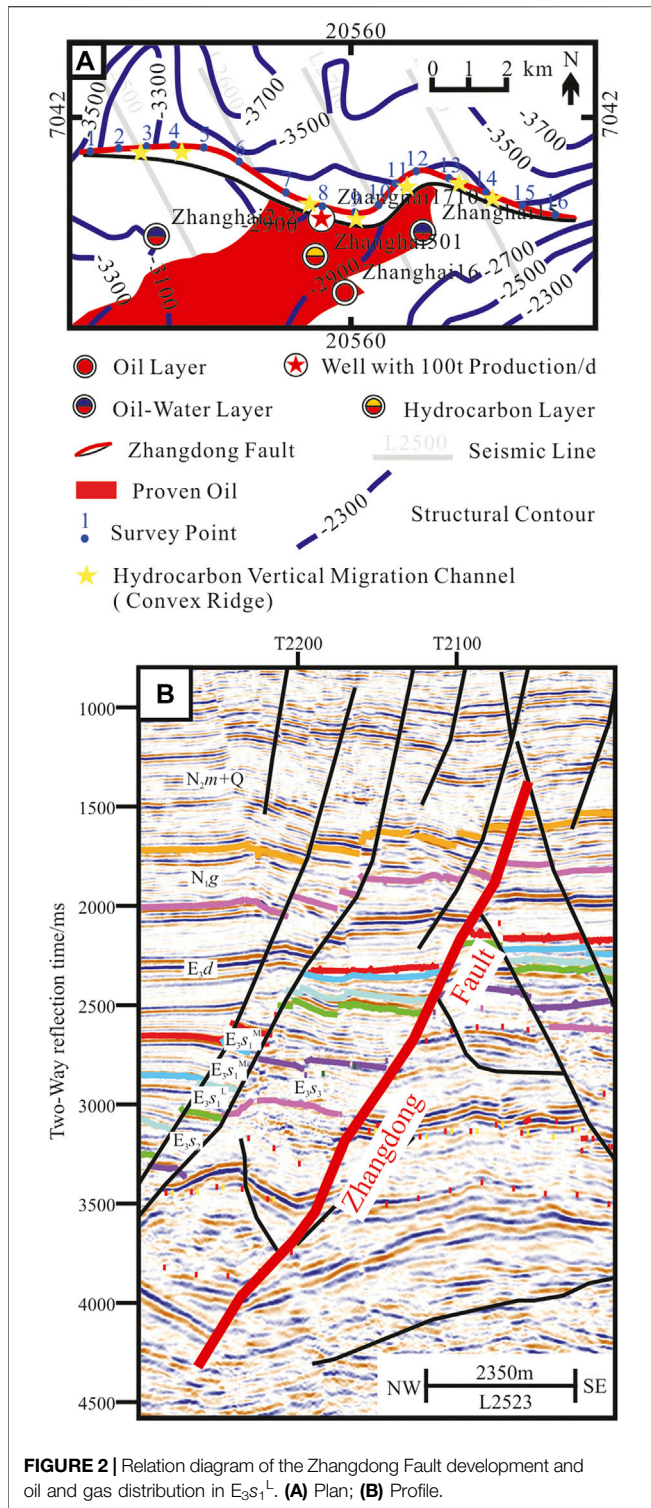
damage degree of the Zhangdong Fault to the regional mudstone caprock in E_{3s1}^M during the hydrocarbon accumulation period, in addition to the influence of trap structure and sand body development. Therefore, an accurate prediction of the damage degree distribution of the Zhangdong Fault to the regional mudstone caprock of E_{3s1}^M during the hydrocarbon accumulation period should be the key for correctly understanding the oil and gas distribution law of E_{3s1}^L near the Zhangdong Fault.

METHODS

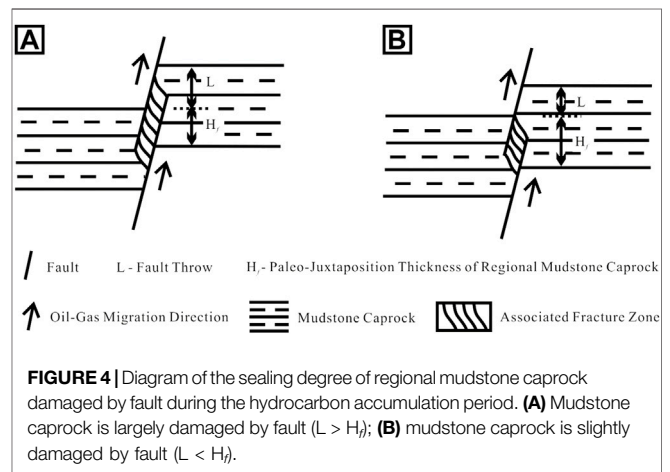
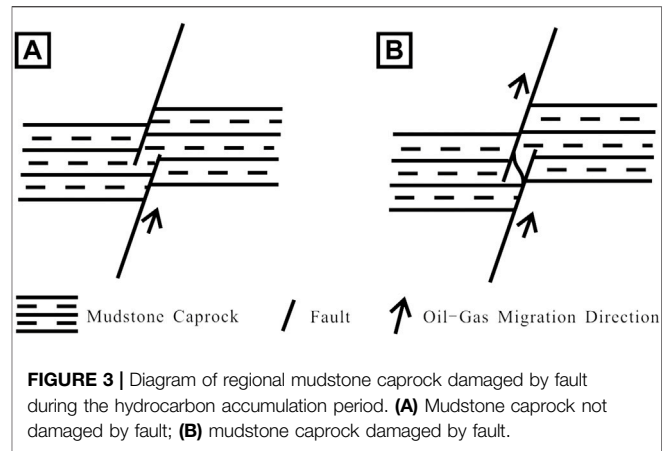
Sealing Mechanism and Degree Distribution Characteristics of Regional Mudstone Caprocks Damaged by Fault During the Hydrocarbon Accumulation Period

A large number of oil and gas exploration practices show that the faults that can damage the regional mudstone caprock are usually relatively large in scale, and these faults are often the transport

channels for oil and gas migration (Zhou et al., 2007; Sun et al., 2012; Fu et al., 2014a). During the hydrocarbon accumulation period, these active faults grow in sections in the regional mudstone caprock, which are connected up and down to become the upward migration channels of oil and gas through the regional mudstone caprock, and the oil and gas under the regional mudstone caprock migrate upward along the fault, so that the sealing capacity of the regional mudstone caprock is damaged by fault, as shown in **Figure 3**. In fact, the process of segmented growth and connection of faults in the regional mudstone caprock is a process of connecting the upper and lower fault-associated fracture zones in the regional mudstone caprock. If the damage degree of the fault to the sealing ability of regional mudstone caprock is different and the connection degree of upper and lower fault-associated fracture zones in the regional mudstone caprock is different, the connectivity of oil and gas transport channels is different, the upward migration characteristics of oil and gas through the regional mudstone caprock along the fault are different, and the sealing degree of the regional mudstone caprock damaged by the fault is also different. The greater the sealing degree of the regional



mudstone caprock damaged by fault, the better the distribution continuity of the connecting zone formed by fault-associated fractures in the regional mudstone caprock and the easier it is for oil and gas under the regional mudstone caprock to migrate upward through the regional mudstone caprock along the fault-associated fracture zone, as shown in **Figure 4A**; on the contrary,



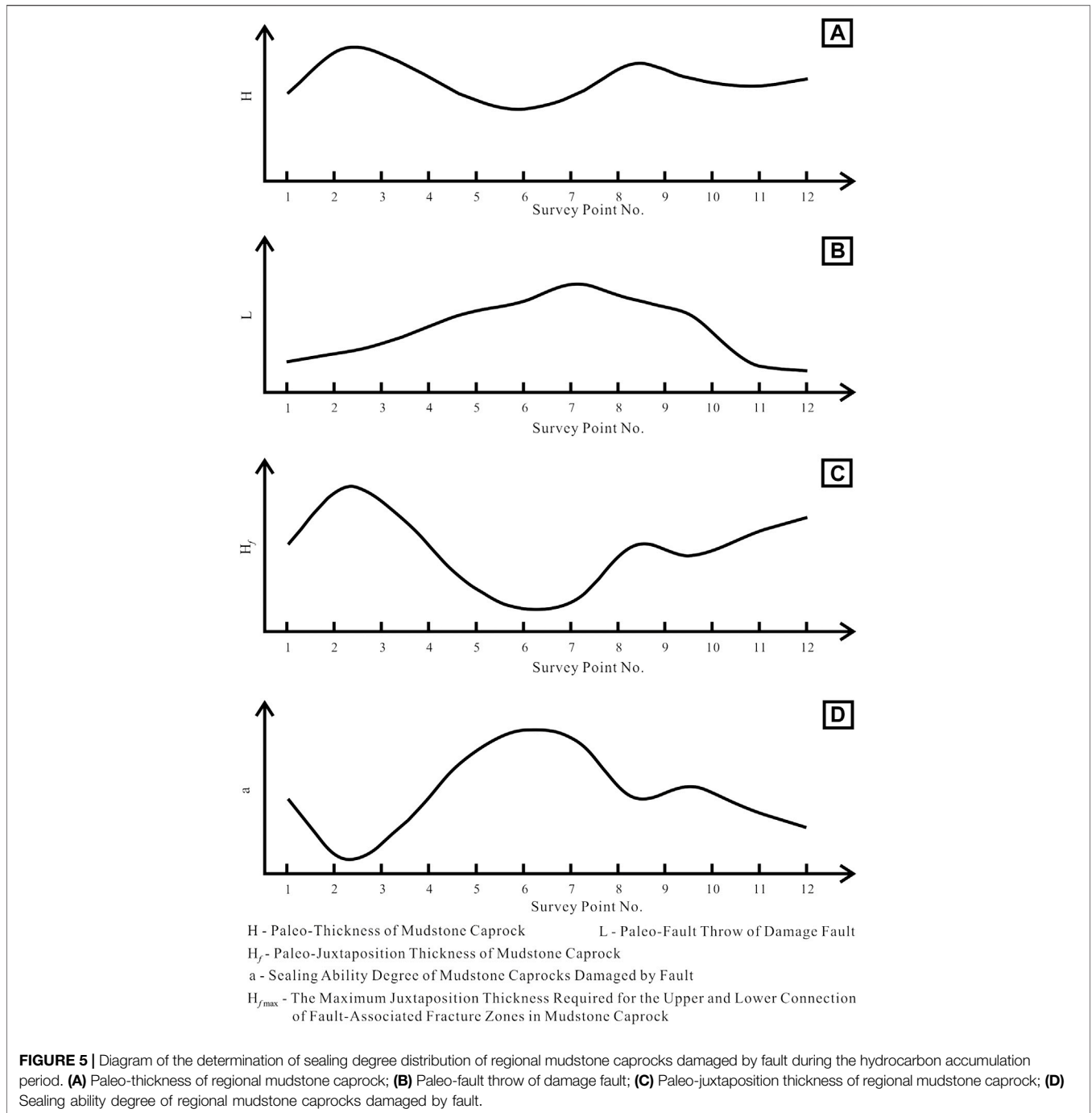
the smaller the sealing degree of the regional mudstone caprock damaged by fault, the poorer the distribution continuity of the connecting zone formed by fault-associated fractures in the regional mudstone caprock and the harder it is for oil and gas under the regional mudstone caprock to migrate upward through the regional mudstone caprock along the fault-associated fracture zone, as shown in **Figure 4B**.

Figure 4 shows that the sealing degree (a) of regional mudstone caprocks damaged by fault during the hydrocarbon accumulation period can be expressed by **Eq. 1** as follows:

$$a = \frac{H_{f \max} - H_f}{H_{f \max}}, \quad (1)$$

where $H_f = H - L$; a—the sealing degree of the regional mudstone caprock damaged by fault during the hydrocarbon accumulation period; $H_{f \max}$ —the maximum juxtaposition thickness required to connect the fracture zone up and down in the regional mudstone caprock, m; H_f —the paleo-juxtaposition thickness of regional mudstone caprock, m; H —the paleo-thickness of mudstone caprock, m; and L —the paleo-fault throw, m.

For the two cases in **Figures 4A,B**, the calculation method of H_f is consistent.



It can be obtained from Eq. 1 that the a-value is directly proportional to the maximum juxtaposition thickness required to connect the fracture zone up and down in the regional mudstone caprock and is inversely proportional to the paleo-juxtaposition thickness of the regional mudstone caprock. The higher the a-value, the greater the damage degree of the fault to the sealing of regional mudstone caprock; otherwise, it is smaller.

This a-value calculation method is only applicable to normal faults. The sealing mechanism of a reverse fault is different from

that of a normal fault and is more complex, which is not suitable for calculating an a-value by this method.

Prediction Method of Sealing Degree Distribution of Regional Mudstone Caprock Damaged by Fault During the Hydrocarbon Accumulation Period

In order to predict the sealing degree distribution of the regional mudstone caprocks damaged by fault during the hydrocarbon

accumulation period, it is necessary to determine the paleo-juxtaposition thickness of regional mudstone caprocks at different parts of fault during the hydrocarbon accumulation period and the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in regional mudstone caprock. The sealing degree distribution of regional mudstone caprocks damaged by fault at different parts during the hydrocarbon accumulation period can be calculated according to **Eq. 1**.

The fault throughgoing horizon in regional mudstone caprock was counted with 3D seismic data, and the faults that are active in the hydrocarbon accumulation period and connect the underlying source rock and regional mudstone caprock were regarded as the faults that damage the regional mudstone caprock. The current thickness of the regional mudstone caprocks broken by the damage faults was counted, and the paleo-thickness during the hydrocarbon accumulation period was restored by the method of stratigraphic paleo-thickness restoration (Tan et al., 2005; Huang et al., 2006; Jiang et al., 2012; Sun et al., 2017), as shown in **Figure 5A**. The method of stratigraphic paleo-thickness restoration refers to the functional relationship that the porosity of clastic rock strata decreases exponentially with the increase of depth according to the principle of constant strata skeleton under normal compaction. On this basis, the paleo-buried depth and paleo-thickness of each stratum in different geological periods can be obtained by strata stripping. Three-dimensional seismic data were applied to count the present fault throw of the damage faults in the regional mudstone caprock, and the paleo-fault throw during the hydrocarbon accumulation period was restored by the maximum fault throw subtraction method (Liu et al., 2012; Wang et al., 2018), as shown in **Figure 5B**. The maximum fault throw subtraction method uses the maximum offset of any point in the fault plane in a set of strata to subtract the maximum fault throw developed in the upper strata and can obtain the paleo fault throw of the fault plane in the sedimentary period. The paleo-juxtaposition thickness of the regional mudstone caprock was calculated by subtracting the paleo-fault throw of the damage fault from the paleo-thickness of the regional mudstone caprock, as shown in **Figure 5C**.

Due to the limitations of current research methods and the quality of seismic data, the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in the regional mudstone caprock cannot be directly determined. It can only be determined indirectly by applying the drilling data to count the paleo-juxtaposition thickness of the regional mudstone caprock at known well points in the study area and the oil and gas display characteristics above and below it and taking the minimum paleo-juxtaposition thickness of the regional mudstone caprock where oil and gas are only distributed below the regional mudstone caprock as the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in the regional mudstone caprocks, as shown in **Figure 6**. If the paleo-juxtaposition thickness of regional mudstone caprock is greater than the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in regional mudstone caprock, oil and gas cannot migrate vertically through

mudstone caprock and can only distribute below the regional mudstone caprock. On the contrary, if the paleo-juxtaposition thickness of regional mudstone caprock is less than the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in regional mudstone caprock, oil and gas will pass through the regional mudstone caprock, which can gather and distribute both below and above the regional mudstone caprock.

By substituting the paleo-juxtaposition thickness of the regional mudstone caprock at different parts of the fault and the maximum juxtaposition thickness required for the upper and lower connection of the fault-associated fracture zone in regional mudstone caprock identified previously into **Eq. 1**, the sealing degree of the regional mudstone caprock damaged by the fault at different parts can be calculated, as shown in **Figure 5D**.

RESULTS AND DISCUSSION

According to the drilling and seismic data, the fault throw of the Zhangdong Fault in the regional mudstone caprock of $E_3s_1^M$ and the thickness of $E_3s_1^M$ regional caprock faulted by the Zhangdong Fault were counted. The paleo-fault throw of the Zhangdong Fault and the paleo-thickness of regional mudstone caprock of $E_3s_1^M$ in the middle and late depositional period of N_2m during the hydrocarbon accumulation period were restored by the maximum fault throw subtraction method (Liu et al., 2012; Wang et al., 2018) and stratigraphic paleo-thickness restoration method (Tan et al., 2005; Huang et al., 2006; Jiang et al., 2012; Sun et al., 2017). By subtracting the former from the latter, the paleo-juxtaposition thickness of the regional mudstone caprock in $E_3s_1^M$ was calculated, as shown in **Figure 7**. It can be seen from **Figure 7** that the paleo-juxtaposition thickness of the regional mudstone caprock of $E_3s_1^M$ in the Zhangdong Fault is relatively large in the middle west parts, the paleo-juxtaposition thickness of $E_3s_1^M$ in the east and west is relatively small, the local paleo-juxtaposition thickness in the east and west is less than zero, and the minimum paleo-juxtaposition thickness can reach more than -165 m in the east.

The relationship between the paleo-juxtaposition thickness of the regional mudstone caprock in $E_3s_1^M$ of Qikou Sag in the middle and late depositional periods of N_2m during the hydrocarbon accumulation period and its upper and lower oil and gas distribution was counted with drilling data, as shown in **Figure 8**. The minimum paleo-juxtaposition thickness when oil and gas are only distributed under the regional mudstone caprock of $E_3s_1^M$ was taken as about 165 m, which is the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in the regional mudstone caprock of $E_3s_1^M$.

By substituting the paleo-juxtaposition thickness of $E_3s_1^M$ at different parts of the Zhangdong Fault and the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in the regional mudstone caprock of $E_3s_1^M$ into **Eq. 1**, the damage degree distribution of the regional mudstone caprock of $E_3s_1^M$ at different parts of the Zhangdong Fault can be calculated, as shown in **Figure 9**. **Figure 9** indicates that the regional

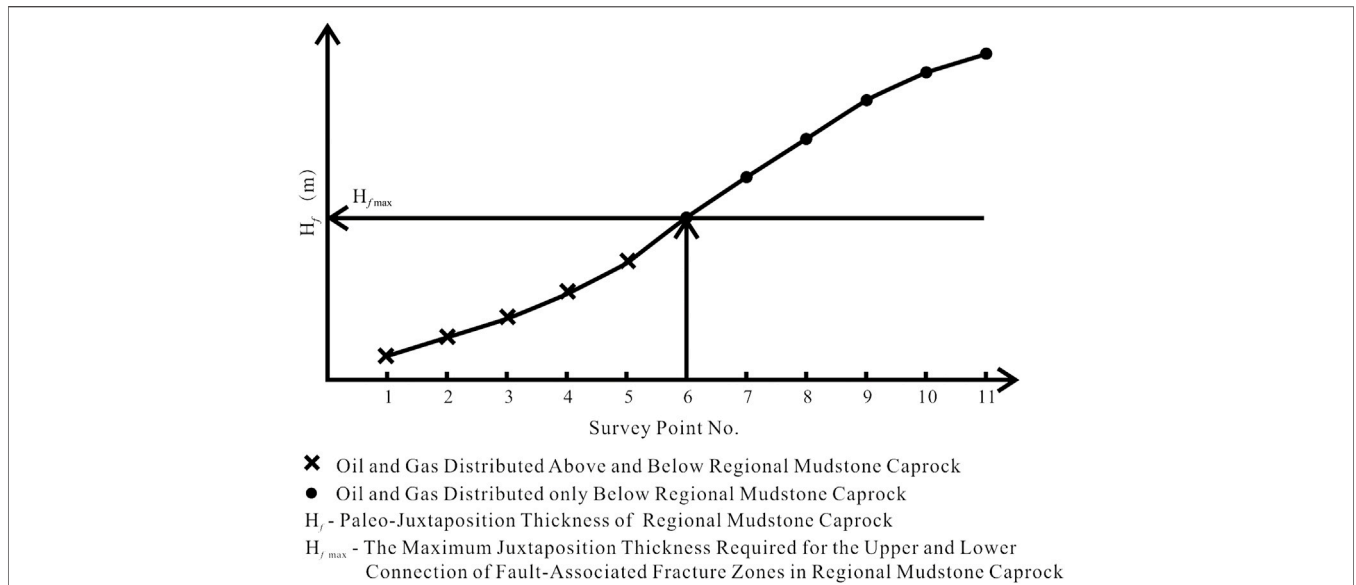


FIGURE 6 | Diagram of the determination of the maximum juxtaposition thickness required for the upper and lower connection of the fault-associated fracture zone in regional mudstone caprock.

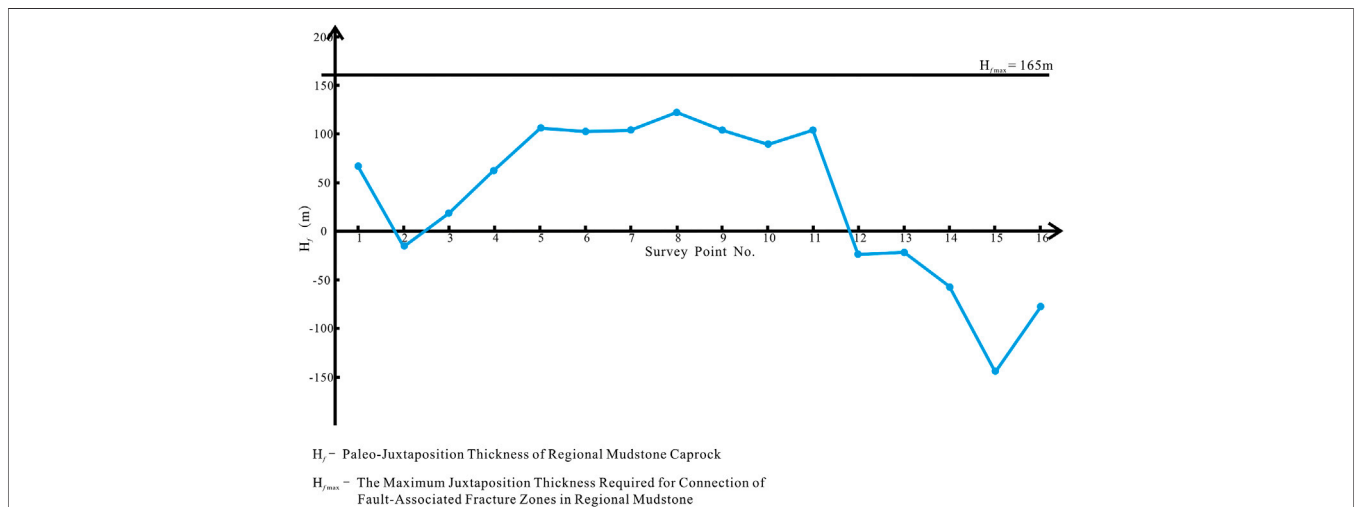


FIGURE 7 | Paleo-juxtaposition thickness distribution of the regional mudstone caprock of $E_{3s_1}^M$ in the Zhangdong Fault during the hydrocarbon accumulation period.

mudstone caprock of $E_{3s_1}^M$ was completely damaged by the Zhangdong Fault in the middle and late depositional periods of the Minghuazhen Formation during the hydrocarbon accumulation period, but different parts exhibited different damage degrees. The Zhangdong Fault in the east has the greatest damage to the regional mudstone caprock of $E_{3s_1}^M$, with an a -value greater than 1, followed by the west end, where the damage degree a -value of the Zhangdong Fault to the regional mudstone caprock of $E_{3s_1}^M$ is more than 0.5, and the maximum is more than 1. The Zhangdong Fault in the middle has the least damage to the regional mudstone caprock of $E_{3s_1}^M$, with an a -value less than 0.5.

According to **Figure 2A**, oil and gas discovered in $E_{3s_1}^L$ near the Zhangdong Fault are mainly distributed in its middle part, which is just the distribution part where the regional mudstone caprock of $E_{3s_1}^M$ was slightly damaged by the Zhangdong Fault during the hydrocarbon accumulation period (as shown in **Figure 9**). Because only in this part, the oil and gas generated and discharged from the source rock of underlying E_{3s_3} migrate to $E_{3s_1}^L$ along the Zhangdong Fault and then migrate upward through the regional mudstone caprock of $E_{3s_1}^M$, with relatively less lost oil and gas, which is conducive to the accumulation and preservation of oil and gas in $E_{3s_1}^L$, and thus oil and gas can be found by drilling; otherwise, no oil and gas will be found.

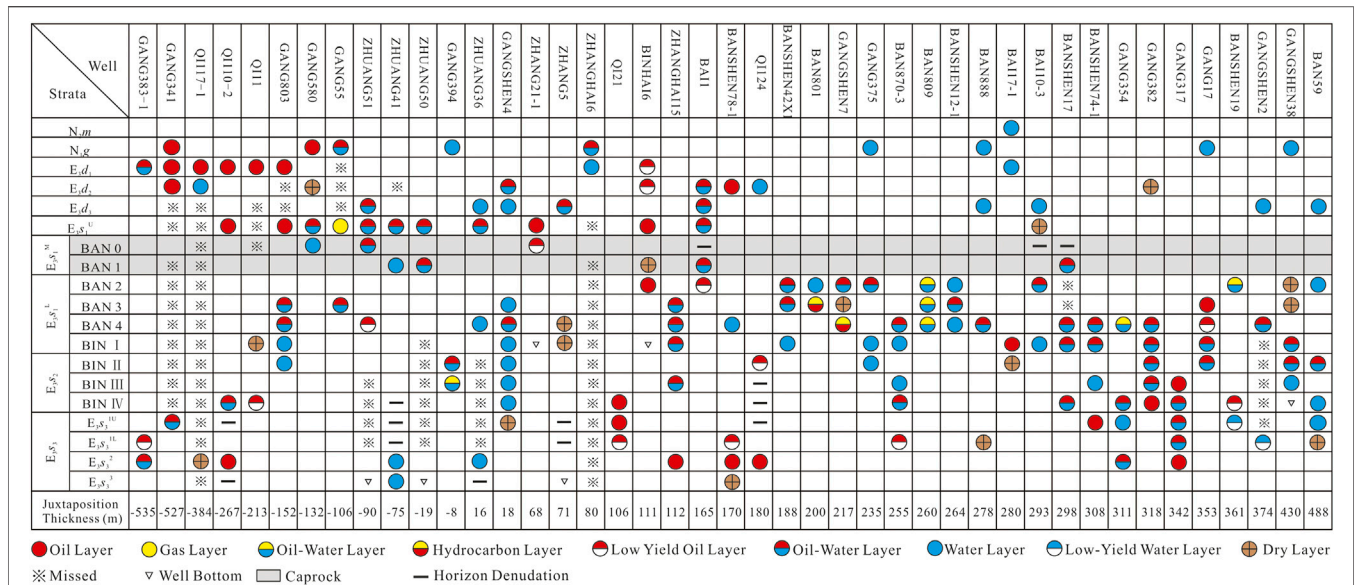


FIGURE 8 | Diagram of the determination of the maximum juxtaposition thickness required for upper and lower connection of fault-associated fracture zones in regional mudstone caprock of $E_3s_1^M$ in Qikou Sag.

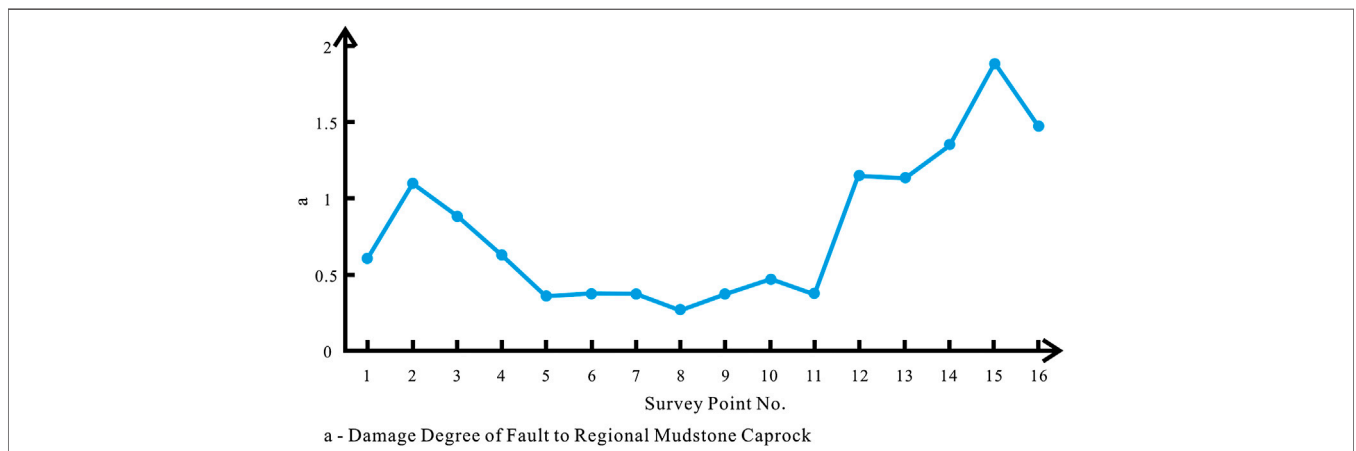


FIGURE 9 | Damage degree of the Zhangdong Fault to the regional mudstone caprock of $E_3s_1^M$ during the hydrocarbon accumulation period.

CONCLUSION

1) The degree of sealing ability of regional mudstone caprock damaged by fault during the hydrocarbon accumulation period is primarily affected by the relative size of the paleo-juxtaposition thickness of regional mudstone caprock and the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in regional mudstone caprock. The smaller the paleo-juxtaposition thickness of regional mudstone caprock, the greater the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in regional mudstone caprock and the larger the sealing capacity degree of regional mudstone caprock damaged by fault; otherwise, it is smaller.

2) The paleo-juxtaposition thickness of regional mudstone caprock was calculated by determining the paleo-fault throw of faults and the paleo-thickness of regional mudstone caprocks during the hydrocarbon accumulation period. Based on the relationship between the paleo-juxtaposition thickness of regional mudstone caprocks at known well points in the study area and the distribution of oil and gas above and below the regional mudstone caprock, the maximum juxtaposition thickness required for the upper and lower connection of fault-associated fracture zones in the regional mudstone caprock was determined. On this basis, a set of prediction methods for the sealing capacity of regional mudstone caprocks damaged by fault during the hydrocarbon accumulation period was established. The practical

application proves that this method is feasible to predict the sealing ability distribution of regional mudstone caprocks damaged by fault during the hydrocarbon accumulation period.

- 3) The damage degree of the Zhangdong Fault to the regional mudstone caprock of $E_3s_1^M$ in the middle and late depositional periods of N_2m in Qikou Sag of the Bohai Bay Basin during the hydrocarbon accumulation period is large; the largest damage appears in the east, with an a -value greater than 1, followed by the west, with an a -value between 0.5 and 1; the least damage occurs to the middle part, with an a -value less than 0.5. The middle part is conducive to the accumulation and preservation of oil and gas generated from the source rock of E_3s_3 in $E_3s_1^L$, which is consistent with the fact that oil and gas discovered in $E_3s_1^L$ near the Zhangdong Fault are mainly distributed in its middle part.
- 4) This method mainly applies to the prediction of the sealing ability degree of regional mudstone caprocks damaged by normal faults in sand-mudstone petroliferous basins during the hydrocarbon accumulation period.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XH contributed to the idea and writing of this manuscript. GF contributed to supervision and funding acquisition. ML contributed to writing-review and editing. FJ, GH and WJ contributed to review and writing of the revised manuscript. All authors contributed to manuscript revision and approved it for publication.

FUNDING

This research was supported by the Joint Funds of National Natural Science Foundation of China (Grant No.41872157, No.42072157, No.41872153 and No.42102165).

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Conflict of Interest: Authors FJ, GH, and WJ were employed by the company PetroChina Dagang Oilfield Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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