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Fault Evolution and Its Effect on the Sealing Ability of Mudstone Cap Rocks

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Abstract: To study the spatial distribution and scale of oil and gas near faults in petroliferous basins, a prediction model is established for the degree of damage that faults in different stages of evolution exert on the sealing ability of mudstone cap rocks by calculating the stages and degree of fault damage to the sealing ability of mudstone cap rocks. This model is applied to the Nanpu 5th Structure and the results show that at survey lines L2 and L8, the F1 Fault destroyed the sealing capacity of mudstone cap rock of the 2nd member of Dongying Formation (E_3d_2). The undamaged cap rock stage, when the degree of damage was zero, persisted from 23.8 to 16.0 Ma at survey line L2 and from 23.8 to 13.6 Ma at survey line L8. Complete destruction, i.e., where the degree of damage was 100%, at survey lines L2 and L8 occurred from 16.0 to 13.3 Ma and from 13.6 to 13.3 Ma, respectively. The partial destruction stage began 13.3 Ma ago and persists today; the degrees of damage at survey lines L2 and L8 were 89.96% and 82.58%, respectively. This was not conducive to oil and gas accumulation in the reservoir under the mudstone cap rock of E_3d_2. These results agreed with the current findings of small amounts of oil and gas under the mudstone cap rock of E_3d_2 at survey line L8 and no oil and gas at survey line L2. This indicates that the model is feasible for predicting the degree of damage to the sealing ability of the mudstone cap rocks by faults at different stages in their evolution.

Keywords: fault evolution; degree of damage; sealing ability; mudstone cap rock; prediction model

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1. Introduction

Mudstone cap rocks control the spatial distribution [1–4] and scale [5,6] of oil and gas accumulation in petroliferous basins. However, whether a mudstone cap rock can seal-in oil and gas is not just related to its own development characteristics [7,8], it also depends on the destructive effect and degree of damage exerted via fault evolution [9–14]. The greater the degree of damage that faults inflict on the sealing ability of mudstone cap rocks, the smaller the scale of oil and gas accumulation in the reservoir under the mudstone cap rock, and vice versa [15–17]. This displays that precisely ascertaining the degree of damage to the sealing ability of mudstone cap rocks exerted by faults in different stages of their evolution is crucial for improving the current comprehension of the role of faults in petroliferous basins in oil and gas accumulation, as well as in steering hydrocarbon exploration.

Two significant aspects are summarized here from previous research on the effects of fault damage on mudstone cap rocks. First, the effect of fault damage on the distribution continuity of mudstone cap rocks is studied by comparing the relative size between the fault throw and the thickness of mudstone cap rocks [18–23]. If the former is greater than the latter, the faults completely stagger the mudstone cap rocks and destroy their distribution continuity. If, however, the mudstone cap rocks are not completely staggered, and because the shale content and degree of diagenetic compaction of the fault rocks are lower than for the mudstone cap rocks, the distribution continuity of the mudstone cap rocks is partially damaged. Second, in the light of the comparative magnitude of the displacement pressure of the fault rocks and the mudstone cap rocks, the impact of fault damage on the closure ability of mudstone cap rocks is studied [10,24–29]. The general assumption is that the greater the displacement pressure of the fault rocks relative to the mudstone cap rocks, the lesser the damage to the closure ability of the mudstone cap rocks by the faults, and vice versa.

However, few studies examine the degree of damage that faults exert on the sealing ability of mudstone cap rocks, and no available studies have assessed how the sealing capacity of mudstone caprocks can be destroyed by faults during different stages of their evolution. This undoubtedly affects the accuracy of studies on the sealing ability of fault-damaged mudstone cap rocks and brings certain perils to hydrocarbon exploration. Consequently, here we try to establish a prediction model for the degree of damage that faults in different stages of evolution exert on the sealing ability of mudstone cap rocks based on the mechanism of faulting, so as to predict the spatial distribution and scale of hydrocarbon near faults in petroliferous basins more accurately.

2. Geological Setting

Located in the northwestern part of the Nanpu Sag, with a structural low in the east and a structural high in the west, the Nanpu 5th Structure covers an exploration area of about 350 km^2 (Figure 1a). It is a buried-hill drape-fold anticline that developed on the background Mesozoic and Paleozoic bedrock nose structures. It is controlled by the Xi'nanzhuang Fault and its derived faults [30], and a series of NEE-trending faults are developed on it (Figure 1a). The strata, developed from bottom to top in this structure, include the Paleogene Kongdian Formation (E_2k), Shahejie Formation (E_3s), Dongying Formation (E_3d), Neogene Guantao Formation (N_1g), Minghuazhen Formation (N_2m), and Quaternary strata (Q). A large volume of oil and gas was discovered under the mudstone cap rock of the 2nd member of the Dongying Formation (E_3d_2). This comes mainly from the source rocks of the 3rd member of Shahejie Formation (E_3s_3) and the 1st member of the Shahejie Formation (E_3s_1). The cap rock of E_3d_2 is a part of the regional mudstone cap rock, with a maximum thickness of more than 300 m. It is thickest in the eastern part of the Nanpu 5th Structure, gradually reducing to zero in the western part [27]. The F1 Fault is situated in the central part of the Nanpu 5th Structure, and is a normal fault extending NEE (Figure 1a). The fault is inclined to the northwest, with an average dip angle of 25°. The maximum fault throw is 185 m and the minimum is 20 m, from the lower part of the 3rd member of the Dongying Formation (E_3d_3) to the upper part of N_1g (Figure 1b).

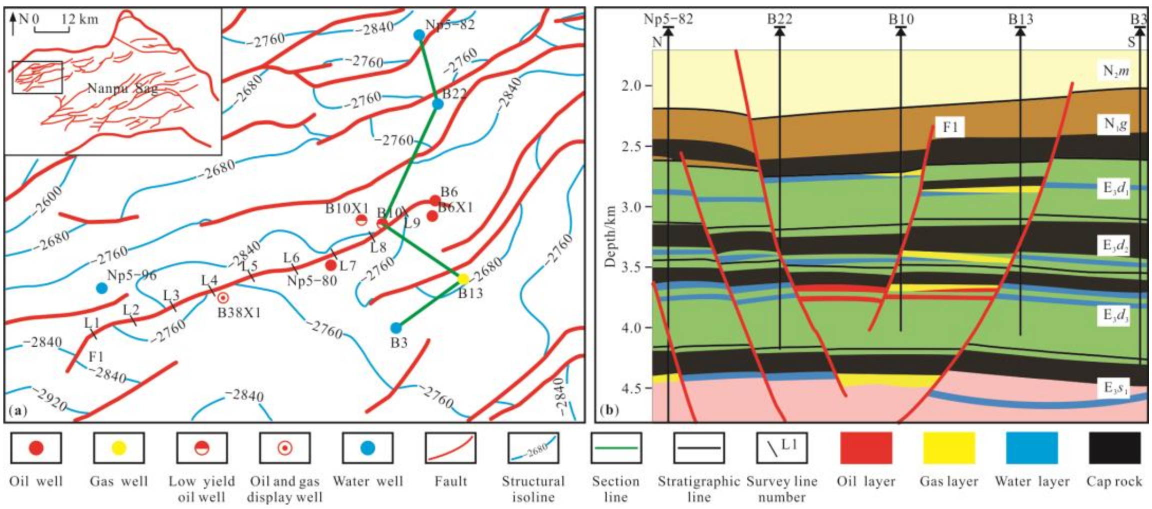

Figure 1. Relationship between the F1 Fault and oil–gas distribution in the Nanpu 5th Structure: (**a**) plan; (**b**) section views.

In the process of the upward migration of oil and gas generated from the source rocks of E_3s_3 and E_3s_1 along the oil source faults (i.e., active faults connecting the source rock of E_3s_3 or E_3s_1 to the reservoir below the mudstone cap rock of E_3d_2 during the hydrocarbon accumulation period in the late-stage sedimentation of N_2m [31]), they will be obstructed by the mudstone cap rock of E_3d_2. Accurately predicting the degree of damage by the F1 Fault to the sealing ability of the mudstone cap rock of E_3d_2 in different stages of fault evolution is crucial for understanding the oil and gas enrichment degree, as well as for the effective guidance of oil and gas exploration below the mudstone cap rock of E_3d_2.

3. Methods

3.1. The Mechanism and Degree of Fault Damage to the Sealing Ability of Mudstone Cap Rocks

The process of fault damage to the sealing ability of mudstone cap rocks is divided into three stages based on the relationship between segmented fault growth in mudstone cap rocks and their effect on the sealing capacity of mudstone cap rocks (Figure 2).

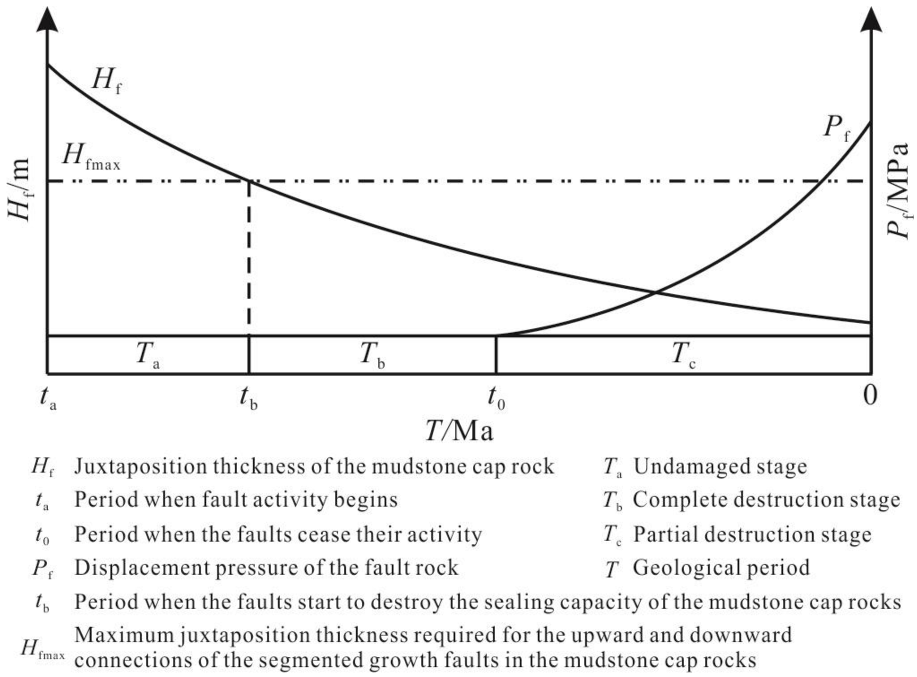

Figure 2. Stages of division of the sealing ability of mudstone cap rocks destroyed by faults.

The first stage is the undamaged stage (T_a), which is the period that marks the beginning of the fault activity (t_a) to when the faults begin to destroy the sealing capacity of the mudstone cap rocks (t_b) (Figure 2). The fault activity is relatively weak at this stage and the fault throw is relatively small. As a result of segmented growth, the faults are not vertically connected and they do not become a transport channel for oil and gas to migrate upward through the mudstone cap rocks. It is believed that faults at this stage do not destroy the sealing capacity of the mudstone cap rocks, and the degree of damage is zero.

The second stage is the complete destruction stage (T_b), which is the period from when the faults begin to destroy the sealing ability of the mudstone cap rocks (t_b) to when their activity stops (t_0) (Figure 2). Unlike in the first stage, the faults that previously experienced segmented growth are now connected; they extend both in the upward and downward directions within the mudstone cap rocks. The gradual increases in fault activity and fault throw make them transport channels for the upward movement of hydrocarbon through the cap rocks. If the degree of damage is 100%, this suggests the complete destruction of the sealing capacity of the mudstone cap rocks.

The third stage is the partial destruction stage (T_c), which begins when the fault activity ceases (t_0) and extends to the present (Figure 2). The cessation of fault activity in conjunction with the overlying sedimentary load, regional principal compressive stress, and mineral precipitation and cementation aided by groundwater results in the sealing of fractures associated with the faults. The fractures lose the ability to transport oil and gas. As the fracture fillers gradually begin to undergo compaction and diagenesis, the fault rocks act as less-effective seals for oil and gas compared to the mudstone cap rocks. As the closure ability of the mudstone cap rocks is partially destroyed by the faults in this stage, the degree of damage is quantitatively expressed as [32]:

$$D = \frac{P_c - P_f}{P_c} \times 100\% \quad (1)$$

where D is the degree of damage (%); P_c is the displacement pressure of the mudstone cap rock (MPa) and P_f is the displacement pressure of the fault rock (MPa).

3.2. Method for Predicting the Degree of Fault Damage to the Sealing Ability of Mudstone Cap Rocks

The above analysis shows that faults at different stages of their evolution exert a different degree of damage to the closure ability of mudstone cap rocks; the method of predicting the degree of damage is also different. Identifying various stages of damage improves predictions of the effect the degree of fault damage has on the sealing ability of mudstone cap rocks.

3.2.1. The Method for Determining the Stages of Damage

It is necessary to determine when the faults were activated, when they started to destroy the sealing capacity of mudstone cap rocks, and when their activity ceased to determine the different stages of fault damage.

The fault growth index [33], fault activity rate [34], and stratigraphic extension rate [35] are used to determine the beginning and ending periods of fault activity. The fault activity period is marked by a fault growth index greater than 1 or by a relatively large fault activity rate or stratigraphic extension rate.

The period when faults begin to destroy the sealing capacity of mudstone cap rocks can be determined according to the following steps. First, the ancient thickness of the mudstone cap rocks during different geological periods is recovered using the ancient thickness resumption method [36] based on calculations of the thickness of the mudstone cap rock and fault throw from the drilling and seismic data. The ancient fault throws from different geological periods are restored using the maximum fault throw subtraction method [19]. The ancient juxtaposition thicknesses of the mudstone cap rocks in different geological periods are calculated by subtracting the ancient fault throw from the ancient mudstone cap rock thickness; the changes in the ancient juxtaposition thickness of the mudstone cap rocks with time are plotted in Figure 2. Second, on the basis of the connection between the juxtaposition thicknesses of the mudstone cap rocks at given well points in the research area and their vertically segregated hydrocarbon distributions, the minimum juxtaposition thickness where the hydrocarbon is only distributed under the mudstone cap rocks is taken as the maximum juxtaposition thickness required for the upward and downward connections of the faults with the segmented growth in the mudstone cap rocks (Figure 3). If the juxtaposition thickness of the mudstone cap rocks exceeds this value, the segmented growth faults will not be vertically connected in the mudstone cap rocks and will not become transport channels for the upward movement of hydrocarbon via the mudstone cap rocks. As a result, oil and gas can only accumulate under the mudstone cap rocks. On the contrary, oil and gas can accumulate above and below the mudstone cap rocks. The faults begin to destroy the sealing capacity of the mudstone cap rocks when the juxtaposition thickness of the mudstone cap rocks is equal to the maximum juxtaposition thickness required for the upward and downward connections of the segmented growth faults in the mudstone cap rocks.

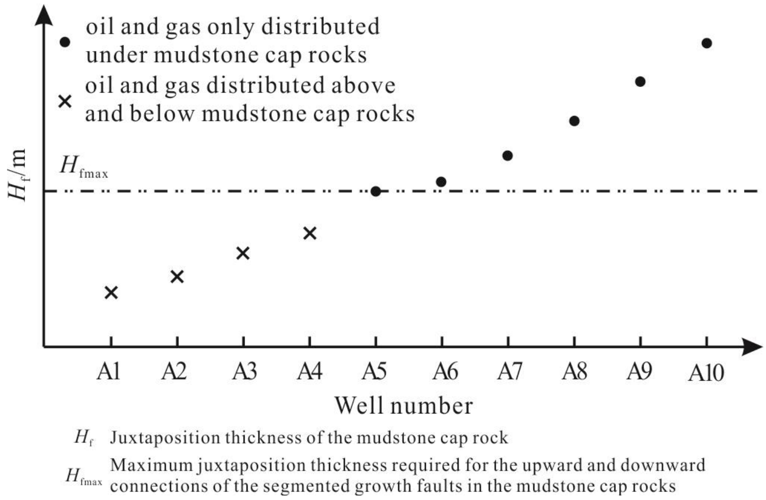

Figure 3. Determination of the maximum juxtaposition thickness required for the upward and downward connections of the segmented growth faults in the mudstone cap rocks.

3.2.2. Determining the Degree of Damage

During different stages of damage, the degrees of damage exerted by the faults to the closure ability of the mudstone cap rocks are dissimilar. In the undamaged stage and the complete destruction stage, the degrees of damage are zero and 100%, respectively. In the partial destruction stage, the degree of damage is related to the displacement pressure of the mudstone cap rocks and the displacement pressure of the fault rocks.

The displacement pressure of the mudstone cap rocks can be obtained via laboratory sampling. In the absence of a sample, a two-parameter empirical formula (Equation (2)) is used. One parameter (Z) is the burial depth of the mudstone cap rocks compacted by diagenesis; if the overlying strata has no obvious uplift and denudation, Z can be replaced by the current burial depth. The second parameter (R) is the shale content obtained from natural gamma logging data [37]:

$$P = a\left(\frac{ZR}{100}\right)^{b} \tag{2}$$

where P is the displacement pressure (MPa), Z is the diagenetic depth of compaction (m), R is the shale content (%), and a and b are region-related parameters.

Although drilling and coring limitations make it impossible to obtain the displacement pressure of fault rocks via the laboratory testing of samples, it can be estimated from the displacement pressure of measured samples of surrounding rocks. For this calculation, it is assumed that the fault is an inclined rock layer embedded in the surrounding rocks, and its material composition comes only from the two adjacent blocks of the faulted strata. Its sealing ability is also affected by the diagenetic depth of compaction and the shale content, just like for the surrounding rocks. On the basis of this assumption, the shale content of the fault rocks is calculated according to the fault throw, as well as the thickness and shale content of the strata, which are staggered by the fault [38]. Substituting the calculation results into Equation (2) gives the relationship between the measured displacement pressure of the surrounding rocks and their diagenetic depth of compaction with the same shale content as the fault rocks (P_s) (Figure 4). The relationship can be extended from the period when the deposition from the surrounding rocks stops (t_s) to the period when the fault rocks begin to undergo compaction (t_0). This defines the relationship between the displacement pressure of the fault rocks and their diagenetic depth of compaction (P_f). Finally, the displacement pressure corresponding to ($z_1\cos\theta$) is taken as the current displacement pressure of the fault rocks (P_{f1}) (Figure 4).

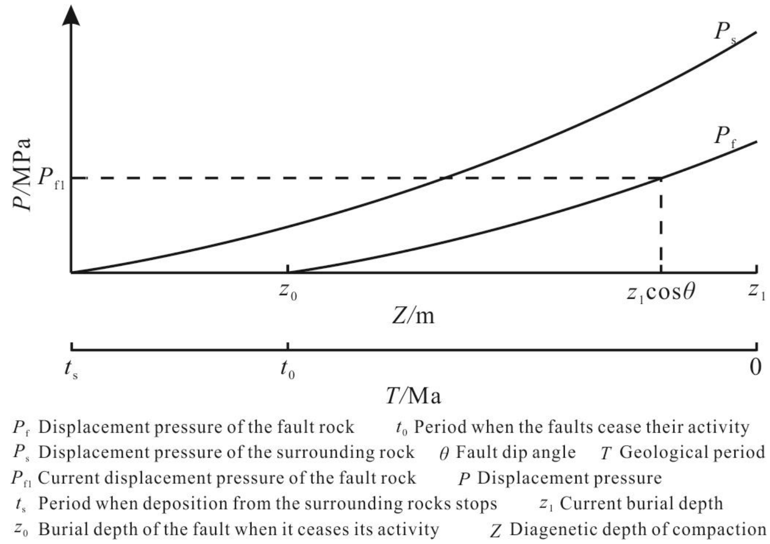

Figure 4. Calculation of displacement pressure of the fault rocks.

The degree of damage that faults impose on the sealing ability of mudstone cap rocks in the partial destruction stage can be estimated by substituting into Equation (1) the displacement pressure of the mudstone cap rocks and their fault rocks as determined above.

4. Results and Discussion

4.1. Stages of Damage

The F1 Fault destroyed the sealing ability of the mudstone cap rock of E_3d_2, but the degree of damage was different at the different survey lines (Figure 1). As shown in Table 1, at survey lines L1, L3, L4, L5, L6, L7, and L9, the juxtaposition thickness of the mudstone cap rock of E_3d_2 overtakes the maximum required for the upward and downward connections of the segmented growth faults in the mudstone cap rocks (about 120 m [28]). Therefore, the F1 Fault has not destroyed the sealing ability of the mudstone cap rock of E_3d_2, i.e., the mudstone cap rock is in an undamaged stage. However, the F1 Fault destroyed the sealing ability of the mudstone cap rock of E_3d_2 where the juxtaposition thickness at survey lines L2 (25 m) and L8 (118 m) is less than the maximum (Table 1). This suggests that it is necessary to study the degree of damage by the F1 fault to the sealing ability of the mudstone cap rock of E_3d_2 in the different stages of fault evolution.

Table 1. Data for the juxtaposition thickness of the mudstone cap rock of E_3d_2.

Survey Lines	L1	L2	L3	L4	L5	L6	L7	L8	L9
Thickness of mudstone cap rock (m)	269	210	243	239	269	305	252	198	290
Fault throw (m)	20	185	110	100	95	100	127	80	50
Juxtaposition thickness of mudstone cap rock (m)	249	25	133	139	174	205	125	118	240

The calculation results for the fault growth index (tantamount to the footwall thickness divided by the hanging thickness of a fault) suggest that the F1 Fault was mainly active during the deposition period of the lower Guantao Formation (N_1g^L), approximately 23.8 to 13.3 Ma (states for millions of years) ago (Figure 5). In other words, the F1 Fault activity began 23.8 Ma ago and ceased about 13.3 Ma ago.

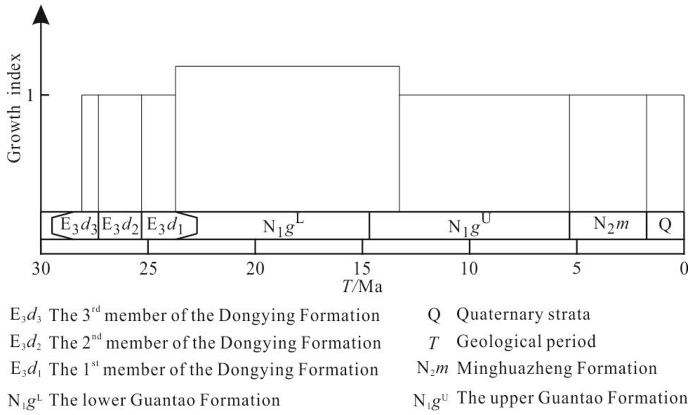

Figure 5. Distribution of the growth index of the F1 Fault in different layers.

Determining when the faults begin to destroy the sealing capacity of the mudstone cap rocks follows, and it can be concluded that approximately 16.0 Ma ago the F1 Fault at survey line L2 began to destroy the sealing capacity of the mudstone cap rock of E_3d_2, while at survey line L8 the destruction began about 13.6 Ma ago (Figure 6).

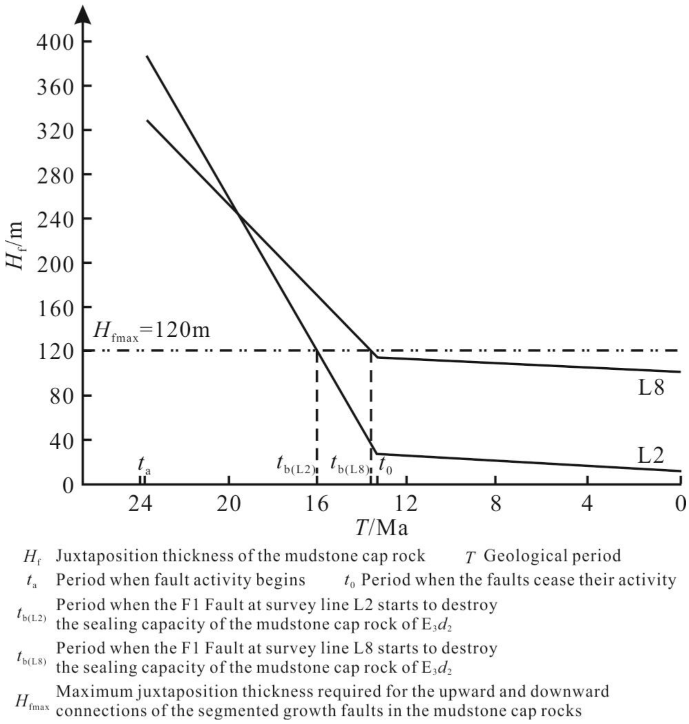

Figure 6. Determination of the period when the F1 Fault begins to destroy the sealing capacity of the mudstone cap rock of E_3d_2.

In summary, at survey line L2, the undamaged stage for the sealing ability of the mudstone cap rock of E_3d_2 was from 23.8 to 16.0 Ma; the complete destruction stage occurred from 16.0 to 13.3 Ma, while the partial destruction stage is ongoing and began 13.3 Ma ago. At survey line L8, the undamaged stage for the sealing ability of the mudstone cap rock of E_3d_2 was from 23.8 to 13.6 Ma, complete destruction occurred from 13.6 to 13.3 Ma, and partial destruction began 13.3 Ma ago and continues today.

4.2. Degree of Damage

The periods between 23.8 Ma and 16.0 Ma and from 23.8 to 13.6 Ma mark the undamaged stage for the sealing ability of the mudstone cap rock of E_3d_2 at survey lines L2 and L8, respectively, i.e., the degree of mudstone cap rock damage by the F1 Fault was zero.

From 16.0 to 13.3 Ma at survey line L2 and from 13.6 to 13.3 Ma at survey line L8, the sealing ability of the mudstone cap rock of E_3d_2 underwent a stage of complete destruction, i.e., the degree of damage was 100%.

The displacement pressures of the mudstone cap rock of E_3d_2 (from Equation (2)), calculated from the relevant parameters listed in Table 2, are about 5.58 MPa and 4.42 MPa at survey lines L2 and L8, respectively. On the basis of this calculation, the current displacement pressures of the fault rocks at survey lines L2 and L8 are calculated to be about 0.56 MPa and 0.77 MPa, respectively (see also Table 2 and Figure 7). Substituting the displacement pressure of the fault rocks and the displacement pressure of the mudstone cap rock of E_3d_2 at survey lines L2 and L8 of the F1 Fault into Equation (1) gives the degrees of damage during the partial destruction stage as 89.96% and 82.58%, respectively (Table 2). Thus, the F1 Fault destroyed the sealing ability of the mudstone cap rock of E_3d_2 to a great extent resulting in the loss of large volumes oil and gas. This is not in favor of the accumulation of oil and gas in the reservoir under the mudstone cap rock of E_3d_2.

Table 2. Calculation of the degree of damage by the F1 Fault to the sealing ability of the mudstone cap rock of E_3d_2 in the partial destruction stage.

Survey Lines	*a*	*b*	Mudstone Cap Rock			Fault Rock			*D* (%)
			***Z* (m)**	***R* (%)**	**P_c (MPa)**	***Z* (m)**	***R* (%)**	**P_f (MPa)**	
L2	0.031 [39]	1.507 [39]	3170.50	98.90	5.58	2873.42	51.38	0.56	89.96
L8			3126.00	86.00	4.42	2833.09	63.80	0.77	82.58

Note: *D* is the degree of damage; P_c is the displacement pressure of the mudstone cap rock; P_f is the displacement pressure of the fault rock; *Z* is the diagenetic depth of compaction; *R* is the shale content; *a* and *b* are region-related parameters.

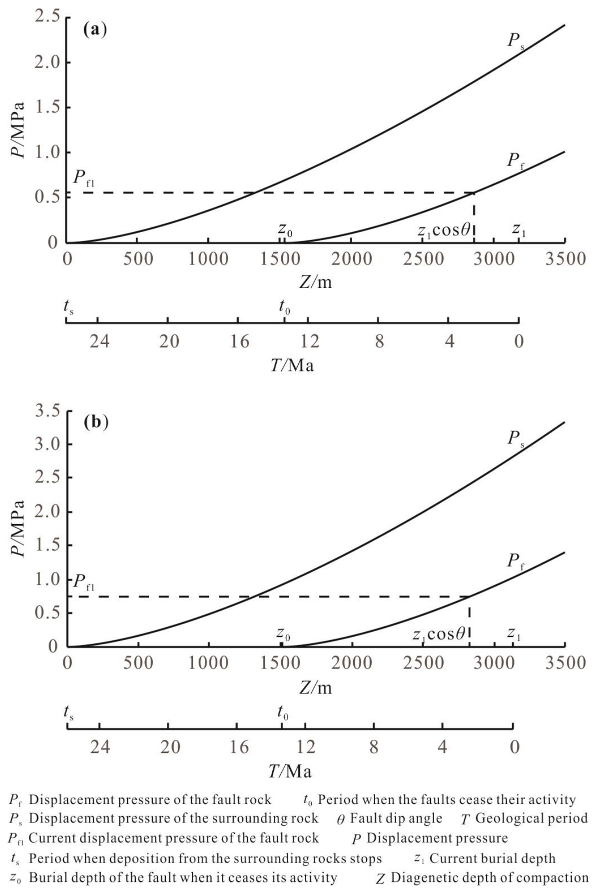

Figure 7. Determination of displacement pressures of the fault rocks at survey lines (**a**) L2 and (**b**) L8.

4.3. Result Verification

The oil and gas drilling results show that well B10 at survey line L8 has obtained low-yield oil flow in the reservoir below the mudstone cap rock of E_3d_2, but the scale is limited, while well Np5-96 at survey line L2 did not yield any oil or gas (Figure 1a). In addition, the F1 Fault has not destroyed the sealing ability of the mudstone cap rock of E_3d_2 at survey lines L4 and L7, and the drilling results show oil and gas (well B38X1) and an oil layer (well Np5-80), respectively. This is consistent with our assessment and indicates that this model is feasible for application in sand and mudstone formations.

5. Conclusions

(1) A prediction model for the degree of damage that faults in different stages of evolution exert on the sealing ability of mudstone cap rocks was established, and the practical application demonstrated the feasibility of this model.
(2) The undamaged stage, i.e., when the degree of damage was zero, was 23.8 to 16.0 Ma ago at survey line L2 and was 23.8 to 13.6 Ma ago at survey line L8. The complete destruction stage, when the degree of damage was 100%, was 16.0 to 13.3 Ma ago at survey line L2 and 13.6 to 13.3 Ma ago at survey line L8. The partial destruction stage began 13.3 Ma ago and persisted to the present; the degrees of damage at survey lines L2 and L8 were 89.96% and 82.58%, respectively.
(3) This model is best suited for predicting the degree of fault damage to the closure ability of mudstone cap rocks in sand and mudstone formations.

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