energies

MDPI

Article

Formation Timing and Features of Stylolites and Controlling Factors for the Second-Period Stylolites in the Carboniferous KT-I Formation of NT Oilfield

Changhai Li [1,*], Lun Zhao [2,*], Weiqiang Li [3], Wenqi Zhao [2], Meng Sun [2], Yu Zhang [3] and Tianyu Zheng [2]

[1] Sinopec International Petroleum Exploration and Production Corporation, Beijing 100029, China
[2] PetroChina Research Institute of Petroleum Exploration and Development, Beijing 100083, China
[3] PetroChina Hangzhou Research Institute of Geology, Hangzhou 310023, China
* Correspondence: chhli.sipc@sinopec.com (C.L.); zhaolun@petrochina.com.cn (L.Z.); Tel.: +86-17-7-7811-8362 (C.L.); +86-13-5-0106-1286 (L.Z.)

Abstract: The formation timing of stylolites, which is of great importance for analyzing the controls of stylolites, has nearly never been examined. In this paper, based on the data of cores, imaging logging, conventional logging, and mercury injection, the characteristics of stylolites formed in different stages of tectonic movement were investigated, and the controlling factors of oil-stained stylolites, formed in the second period of tectonic movement, were analyzed in particular. Furthermore, the influence of different controlling factors on the development of stylolites was compared, by using grey correlation analysis. The results show that there are three periods of stylolites in the study area, and all three periods developed both low-angle stylolites and high-angle stylolites. The prominent characteristics of both the low-angle and high-angle stylolites of the second period, are being oil-stained. The higher the structural location, the greater the buried depth, the lower the dolomite content, the higher the calcite content, the higher the clay content, the smaller the rock density, the greater the porosity, the smaller the rock grain size, the easier it is to develop both the low-angle stylolites and the high-angle stylolites. The influence of different controlling factors on the development of low-angle stylolites is given by depth, porosity, curvature, rock density, rock grain size, clay content, dolomite content, and calcite content, in this order. The importance of the influences on the development of high-angle stylolites proceeds as follows: curvature, calcite content, depth, rock particle size, clay content, rock density, dolomite content, and porosity. Tectonism is the most important influencing factor on the development of stylolites.

Keywords: stylolites; formation timing; controlling factors; KT-I Formation; NT oilfield; carbonate

check for updates

Citation: Li, C.; Zhao, L.; Li, W.; Zhao, W.; Sun, M.; Zhang, Y.; Zheng, T. Formation Timing and Features of Stylolites and Controlling Factors for the Second-Period Stylolites in the Carboniferous KT-I Formation of NT Oilfield. *Energies* **2023**, *16*, 2909. https://doi.org/10.3390/en16062909

Academic Editors: Shifeng Zhang, Liangbin Dou, Wenmin Guo, Guoqiang Xing and Yan Zhuang

Received: 31 January 2023
Revised: 28 February 2023
Accepted: 28 February 2023
Published: 22 March 2023

1. Introduction

Stylolites are common in carbonate reservoirs, and they can affect rock diagenesis and even oil and gas production [1,2]. Stylolites are interlocked interfaces between two surrounding rocks, and clay or organic matter is often accumulated between the two interfaces [3–5]. Previous work has reported that stylolites can form after the buried depth of rock exceeds 100 m [6,7], and they can be continuously produced as the depth increases [8]. Buried rock strata generally undergo multi-stage tectonic evolution, which indicates that the stylolites observed today were formed in multi-stage tectonic movements. The geological conditions in different stages of tectonic movements are remarkably different, and the stylolites formed in different stages of tectonic movements must be different. However, previous studies on stylolites rarely analyzed the formation timing and characteristics of stylolites in different tectonic movements. It is of great significance to study the formation timing of stylolites, for understanding the controlling factors of stylolites' development. So far, a great deal of research has been performed on the controlling factors of stylolites, and the controlling factors can be concluded to be the following: structural location, rock composition, rock grain size, and rock density [9–11]. However, all of these studies only analyzed the influence of present geological conditions on stylolites, ignoring the difference between the present geological conditions and those at the time of the stylolites' formation. Therefore, it is imperative to study the scientific problem of the controlling factors of the development of stylolites, under the control of understanding the formation of geological conditions. In addition, the critical scientific issue, of which is the most important controlling factor for the development of stylolites, has not been answered accurately.

The NT oilfield is located in the eastern margin of the Precaspian Basin. The main producing layer is the Carboniferous KT-I Formation, developing carbonate deposits of restricted platform facies and open platform facies. A large number of stylolites developed in the NT oilfield, and the formation timing of the structural fractures in the NT oilfield has been studied deeply, which provides convenience for studying the formation timing and controlling factors of stylolites. Previous studies mainly focused on sedimentary characteristics [12–15], diagenesis [12,16], and tectonic evolution [17,18] of the study area, but little attention has been paid to the stylolites in the study area. Based on the previous work on the tectonic evolution in the study area, this paper first determined the formation timing of stylolites, and analyzed the developmental characteristics of stylolites in different stages of tectonic movements. Then, the controlling factors of stylolites, with the characteristics of oil stains, formed in the second period of tectonic movement, were studied. Finally, the influence of structural location and depth, rock composition, rock grain size, rock density, and rock porosity on the development of stylolites were compared, to determine the most important controlling factors for the development of stylolites.

2. Geological Setting

The Precaspian Basin, located in the west of Kazakhstan, is one of the deepest subsidence basins in the world, with a maximum sediment thickness of 22 km [19,20]. The basin reaches the Ural orogenic belt in the east, the South Emba fault-related uplift in the southeast, the Caspian Sea in the south, the Donbass–Tuarkyr system of inversion uplift in the southwest, and the Volga–Ural basin in the north [21]. The basin can be divided into four substructural units, including the fault terrace belt in the north and northwest, the central depression zone, the Astrakhan–Aktyubinsk uplift zone, and the southeast depression zone [22]. The Permian Kungurian salt is widespread within the basin, and it divides the basin into pre-salt and post-salt.

The NT oilfield is located on the eastern margin of the Precaspian Basin, and structurally it belongs to the Astrakhan–Aktyubinsk uplift zone (Figure 1a). The study area is an anticline, with the tectonic framework of high in the east and low in the west (Figure 1b). The target zone is the pre-salt Carboniferous KT-I Formation. The KT-I Formation is further subdivided into A1, A2, A3, Б1, Б2, B1, B2, B3, B4, and B5 (Figure 1c,d) [20]. Layer A1 and part of layer A2 were denuded, due to the influence of paleotectonic movements. Layers A1, A2, A3, Б1, and Б2 are characterized by restricted platform facies, with the lithology of limestone and dolomite. Layers B1, B2, B3, B4, and B5 primarily are dominated by open platform facies, with the lithology of limestone. The tectonic evolution in the study area can be divided into three stages [17]: (1) The tectonic movement in the early Permian formed the tectonic framework, of high in the west and low in the east, with a formation dip angle of 10°. (2) The late Permian tectonic movement further intensified the paleotectonic framework, of high in the west and low in the east, and the formation dip angle reached 15°. (3) The tectonic movement in Triassic underwent structural inversion and formed the present tectonic framework, of high in the east and low in the west, with the formation dip angle reaching 25° (Figure 2). The three periods of tectonic movements are dominated by NE-SW compressive tectonic stress. The multi-stage tectonic movements led to the formation of NE-SW trending reverse faults, and the development of a large number of fractures, forming the fracture-porous carbonate reservoir in the study area.

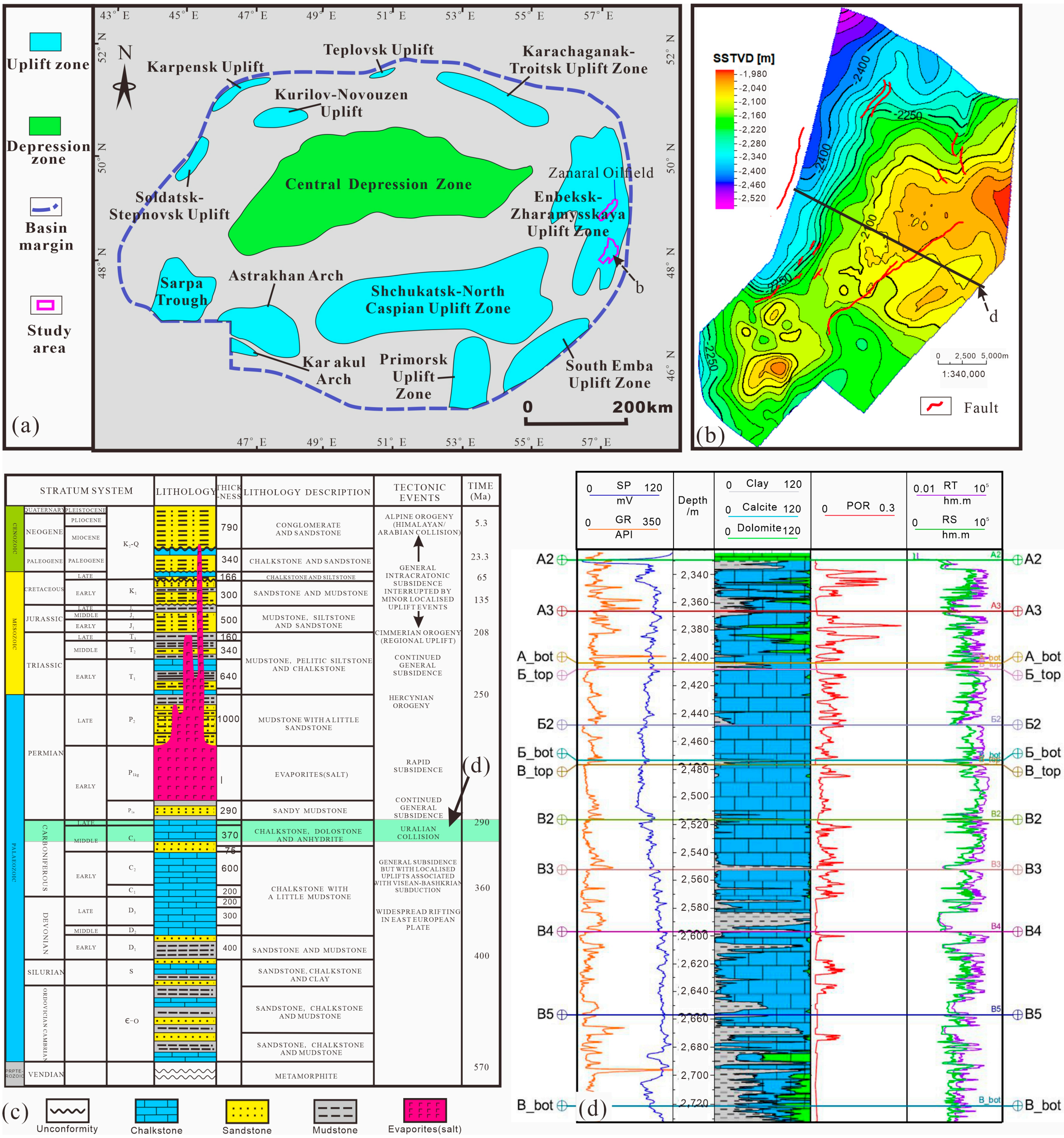

Figure 1. (**a**) Tectonic divisions of Precaspian Basin [23]. (**b**) The structural map of the top of the KT-I Formation. (**c**) Stratigraphic column for the area of study [24]. (**d**) The layer division results of the KT-I Formation in the NT oilfield [25].

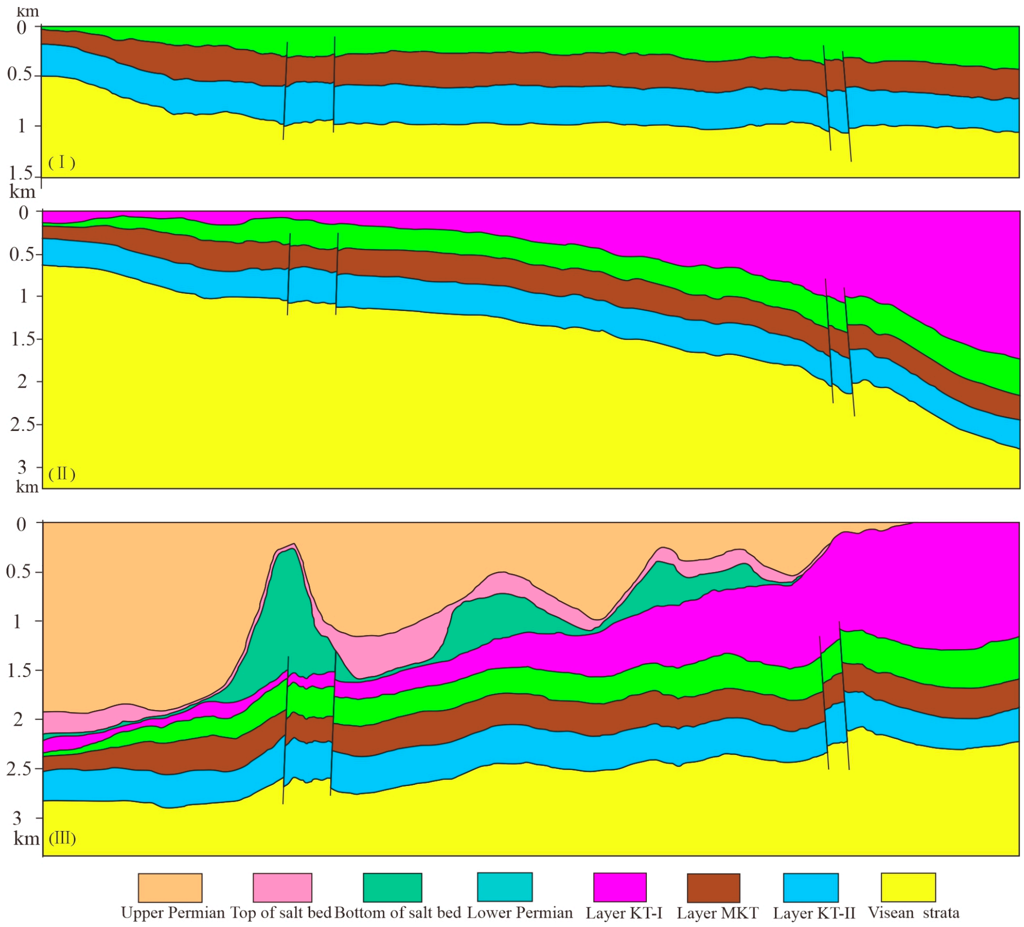

Figure 2. Tectonic evolution of the study area. (**I**) The first-stage tectonic movements in the early Permian. (**II**) The second-stage tectonic movements in the late Permian. (**III**) The third-stage tectonic movements in the Triassic.

3. Methods

3.1. Data Collection

This paper is chiefly based on the data of coring, imaging logging, conventional logging, and mercury injection. A total of 447.55 m of coring intervals, from 17 wells, was obtained in this study. According to the coring data, the filling characteristics and the cutting relationship of stylolites with other fractures were studied, to identify the stylolites in different stages of tectonic movements. There are six full interval imaging logging wells, and they were used to examine the strike of stylolites. Imaging logging interpretation results of stylolites strikes were provided by Schlumberger Ltd., Houston, TX, USA.

All wells with cores or imaging logging have conventional logging data. Conventional logging data include a lithologic interpretation log, density log, and porosity log, which provide a basis for analyzing the influence of rock composition, rock density, and rock porosity on the development of stylolites. The conventional logging interpretation results were provided by PetroChina Petroleum Exploration and the Development Research Institute.

A mercury porosimeter, with a maximum injection pressure of 200 MPa, was applied to analyze the pore throat systems and gain pore throat parameters, to evaluate the rock grain size. This experiment was performed at the Geological Exploration and Development Research Institute of the Former Sichuan Petroleum Administration. A total of 28 mercury injection samples were tested.

3.2. Computing Methods

(1) Calculation of fracture linear density

The linear density of fractures in a single well refers to, the ratio of the number of fractures identified in the cores to the coring length [26], and its calculation formula is:

$$\text{fracture linear density} = \frac{\text{number of fractures in core}}{\text{length of core}}$$

The fracture linear density log is calculated based on the coring data, and its calculation formula is [27]:

$$\text{intensity (depth)} = \frac{\left(\text{cumulative}\left(\text{depth}+\frac{w}{2}\right)\right) - \left(\text{cumulative}\left(\text{depth} - \frac{w}{2}\right)\right)}{w} \quad (1)$$

where intensity (depth) is the fracture density (m^{-1}) of each sampling point of depth, cumulative (depth) is the cumulative number of stylolites of each sampling point of depth, and w is the window length (m). The linear density log of stylolites can be calculated by using the Petrel software, and the default window length of Petrel is 1 m in this study.

(2) Calculation of curvature

Curvature refers to the ratio of the rotation angle of the tangent of any curve to the corresponding arc length. It is a parameter to describe the change in the curve bending degree. The larger the curvature value is, the more curved the curve is [28].

$$K = \frac{d\omega}{dS} = \frac{2\pi}{2\pi R} = \frac{1}{R} \quad (2)$$

where K is the curvature, ω is the rotation angle of the tangent, and S is the tangent moving distance on the arc. A curve can be obtained by cutting a three-dimensional curved surface, by selecting a section, and the curvature of any point on the three-dimensional curved surface can be obtained correspondingly. The direction of the cross-section can be an arbitrary choice, thus any point has countless curvatures for a three-dimensional space surface. However, there exists a maximum value among the countless curvature values, which is defined as the maximum curvature, and recorded as Kmax. The curvature value can also be calculated for the section perpendicular to the section with the maximum curvature, which is defined as the minimum curvature, and recorded as Kmin. The curvature can be calculated in the Petrel software, according to the structural surface.

(3) Calculation of rock grain size by using mercury injection experiment

The relationship between mercury injection pressure and pore throat size during mercury injection, is as follows:

$$P_{Hg} = \frac{2\sigma_{Hg}\cos\theta_{Hg}}{r} \quad (3)$$

where P_{Hg} is the capillary pressure of mercury (unit: MPa), σ_{Hg} is the surface tension of mercury (unit: mN/cm), and θ_{Hg} is the contact angle of mercury in the air. Generally, σ_{Hg} = 480 mN/m and θ_{Hg} = 140° [29]. Therefore, the above formula can be rewritten as:

$$r = \frac{0.75}{P_{Hg}} \quad (4)$$

where r is the median radius of pore throats (unit: μm). When the non-wetting phase (refers to the mercury) saturation is 5%, the corresponding pore throat radius is r_5, which is used to measure the average rock grain size.

(4) Principle and process of grey correlation analysis

Grey correlation analysis determines whether the sequence curves are closely related, according to the similarity degree of their geometric shapes. The closer the curves are, the greater the grey relational grade between the corresponding sequences is, and vice versa. The grey correlation analysis can effectively compare the influence of various factors on the results [30]. The grey relational grade was applied, to evaluate the influence of different controlling factors, including curvature, depth, calcite content, dolomite content, clay content, rock density, porosity, and r_5 on the development of stylolites in this paper. The analysis steps of grey relational analysis are as follows [31]:

Step 1: Determination of analysis sequence

Set the dependent variable to be the referential series and the independent variable to be the compared series, and it can be expressed as:

$$Y(\text{target}) = (Y(1), Y(2), \cdots, Y(n)) \tag{5}$$

$$X_i(\text{indexes}) = (X_i(1), X_i(2), \cdots, X_i(n)) \tag{6}$$

where Y (target) is the referential series, X_i (indexes) is the compared series, n is the sequence length, and i = 1, 2, . . . , M, where M is the number of subsequences.

Step 2: Dimensionless raw data

The dimensions of the raw data are not necessarily the same, due to the difference in physical attributes of different factors in the system, leading to difficulties in making a direct comparison or obtaining a correct conclusion. Therefore, it is necessary to perform dimensionless processing on the data before carrying out the grey correlation analysis. The z-score standardized method for dimensionless data, was adopted in this paper.

$$X_i^* = \frac{X_i - \overline{X}}{\sigma} \tag{7}$$

where X_i^* is the standardized value, $\overline{X}$ is the average value, and σ is the standard deviation.

Step 3: Grey relational coefficient calculation

The grey relational coefficient is essentially the difference degree of geometric shapes between curves. Therefore, the difference between curves can be evaluated by the grey relational coefficient. There are several compared series X1, X2, . . . , Xn, for a referential series Y, and the grey relational coefficient, ξ (X_i), between each compared series and the referential series at each time (i.e., each point in the curve) can be calculated by the following formula:

$$\varepsilon_{0i}(j) = \frac{\Delta\min + \rho\Delta\max}{\Delta_{0i}(j) + \rho\Delta\max} \tag{8}$$

where $\varepsilon_{0i}(j)$ is the grey relational coefficient. $\Delta_{0i}(j) = |Yj - X_i(j)|$ is the absolute difference between the referential series and the compared series, at time j. Δmax and Δmin are the maximum and minimum values of the absolute difference between the referential series and the compared series; ρ is the resolution coefficient, generally between 0 and 1, and it usually takes 0.5 [32]. A value of 0.5 was used in this study.

Step 4: Grey relational grade calculation

$$r_{0i}(j) = \frac{1}{n}\sum_{j=1}^{n}\varepsilon_{0i}(j) \tag{9}$$

where $r_{0i}(j)$ is the grey relational grade. The grey relational grade reflects the similarity between the referential series and the compared series. The greater the grey relational grade is, the greater the influence of the compared series on the referential series. Grey relational analysis can be realized in the DPS software.

4. Results

4.1. Formation Timing and Characteristics of Stylolites

4.1.1. Characteristics of Stylolites Formed in Different Tectonic Movements

The NT oilfield has experienced three-stage tectonic movements [17]. According to the cutting relationship between stylolites and bedding-parallel fractures, and the filling characteristics of stylolites, the developmental characteristics of stylolites formed during the different tectonic movements in the study area were analyzed. The classification of stylolites put forward by Park et al. [33], according to the two-dimensional geometry of stylolites, was applied in this study to describe the characteristics of stylolites (Figure 3).

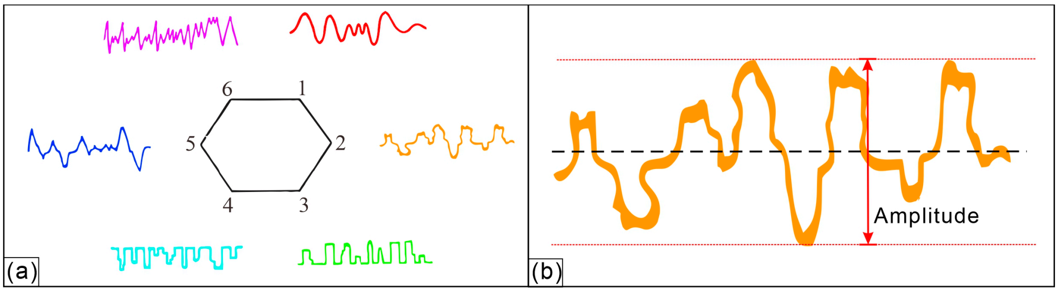

Figure 3. Classification and amplitude of stylolite. (**a**) Classification of stylolite according to the two-geometry of the stylolite itself [29]. 1. Simple or primitive wave-like type; 2. sutured type; 3. up-peak type (rectangular type); 4. down-peak type (rectangular type); 5. sharp-peak type (tapered and pointed); 6. "seismogram" type. (**b**) Amplitude of stylolite.

In this study, the criteria of the dip angle of stylolites, for dividing into high-angle stylolites and low-angle stylolites, was 30°. Both low-angle stylolites and high-angle stylolites developed in all three-stage tectonic movement. Low-angle stylolites, also named sedimentary stylolites, are formed due to compaction and deformation of sedimentary rocks [34]. High-angle stylolites, also named tectonic stylolites, are developed because of the interaction of rock layers with tectonic forces such as faulting and folding [34]. The low-angle bedding-parallel fractures in the study area were formed in the second period of tectonic movement [24]. And the low-angle bedding-parallel fractures pinch out at the low-angle stylolites, indicating that the stylolites developed earlier than the bedding-parallel fractures, formed in the second period of tectonic movement (Figure 4a and Table 1). Thus, it is inferred that the low-angle stylolites were formed in the first period of tectonic movement. The low-angle stylolites of the first period are characterized by the sharp-peak shape, with an amplitude of 1.768 cm. The amplitude of the low-angle stylolites of the first period is the largest among the three periods for low-angle stylolites. The typical identification feature of the high-angle stylolites of the first period, is that they are cut by low-angle bedding-parallel fractures. The high-angle stylolites of the first period feature primitive wave-like shapes, and their amplitudes are only 0.448 cm, which is the smallest among the three periods for the high-angle stylolites (Figure 4b and Table 1).

The oil emplacement in the study area occurred in the late period of the second tectonic movement [35–37], and thus the prominent characteristics of both the low-angle and the high-angle stylolites of the second period are filled by oil. The low-angle stylolites of the second period are primitive wave-like, with a small amplitude, of only 0.852 cm (Figure 4c and Table 1). The high-angle stylolites of the second period are sutured, and their amplitudes are the largest in the three periods for high-angle stylolites, reaching 1.252 cm (Figure 4d and Table 1).

The typical feature of the low-angle stylolites of the third period is unfilled, with the nearby low-angle bedding-parallel fractures filled by oil (Figure 4e). This suggests that the stylolites were formed later than the oil filling. The low-angle stylolites of the third period are up-peak, with a relatively large amplitude, of 1.054 cm (Figure 4e and Table 1). The high-angle stylolites of the third period pinch out at the oil-stained low-angle stylolites of the second period, and are not filled with oil, demonstrating that the high-angle stylolites of the third period formed later than the oil filling. The amplitude of the third-period high-angle stylolites is only 0.642 cm (Figure 4f and Table 1).

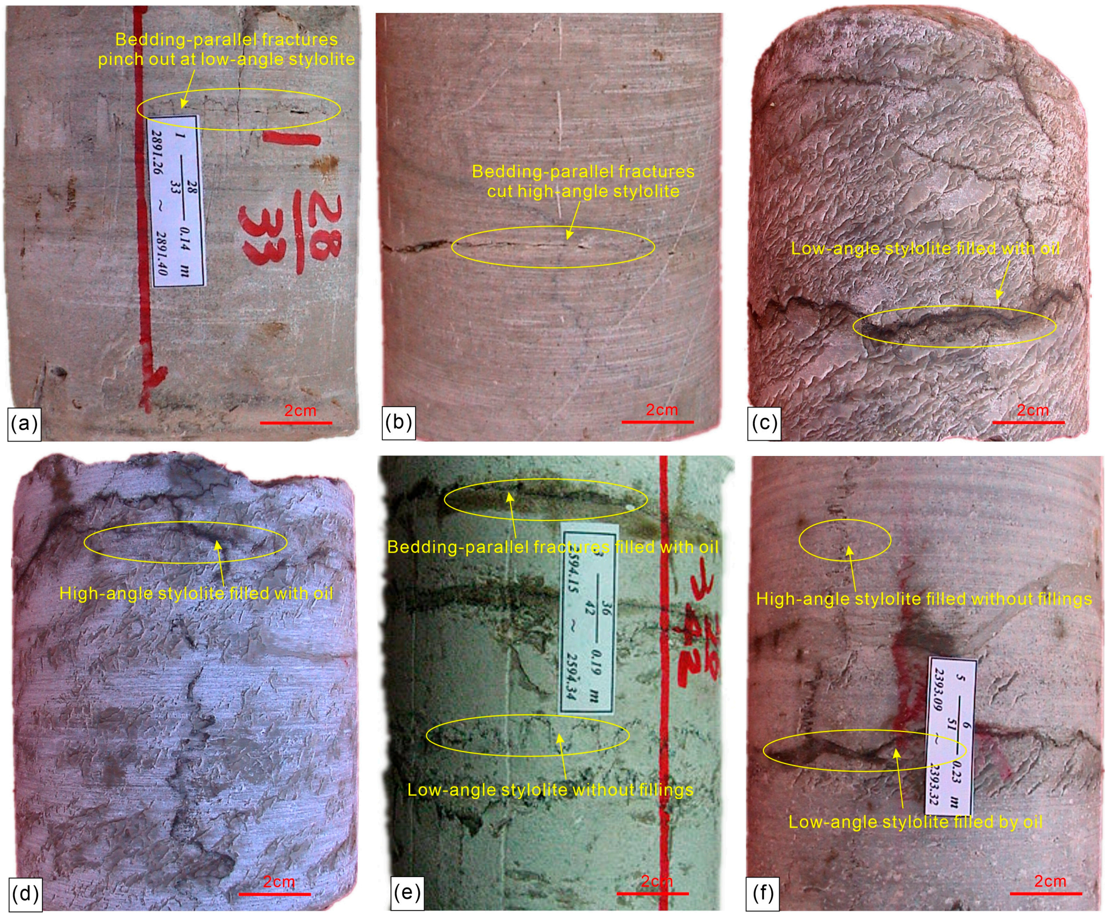

Figure 4. Characteristics of stylolites formed in different stages of the tectonic movements in the NT oilfield. (**a**) Low-angle stylolite formed in the first period of tectonic movement. (**b**) High-angle stylolite formed in the first period of tectonic movement. (**c**) Low-angle stylolite formed in the second period of tectonic movement. (**d**) High-angle stylolite formed in the second period of tectonic movement. (**e**) Low-angle stylolite formed in the third period of tectonic movement. (**f**) High-angle stylolite formed in the third period of tectonic movement.

Table 1. Comparison of quantitative parameters of stylolites formed in different stages of the tectonic movements in the NT oilfield.

	Stylolite of the First Period		Stylolite of the Second Period		Stylolite of the Third Period	
	Amplitude	**Reference Picture**	**Amplitude**	**Reference Picture**	**Amplitude**	**Reference Picture**
Low-angle stylolite (cm)	1.768	Figure 4a	0.852	Figure 4c	1.054	Figure 4e
High-angle stylolite (cm)	0.448	Figure 4b	1.252	Figure 4d	0.642	Figure 4f

Based on the tectonic evolution of the basin in the study area, and the analysis results of the formation periods of the stylolites, the evolution pattern of stylolites in the study area was established (Figure 5).

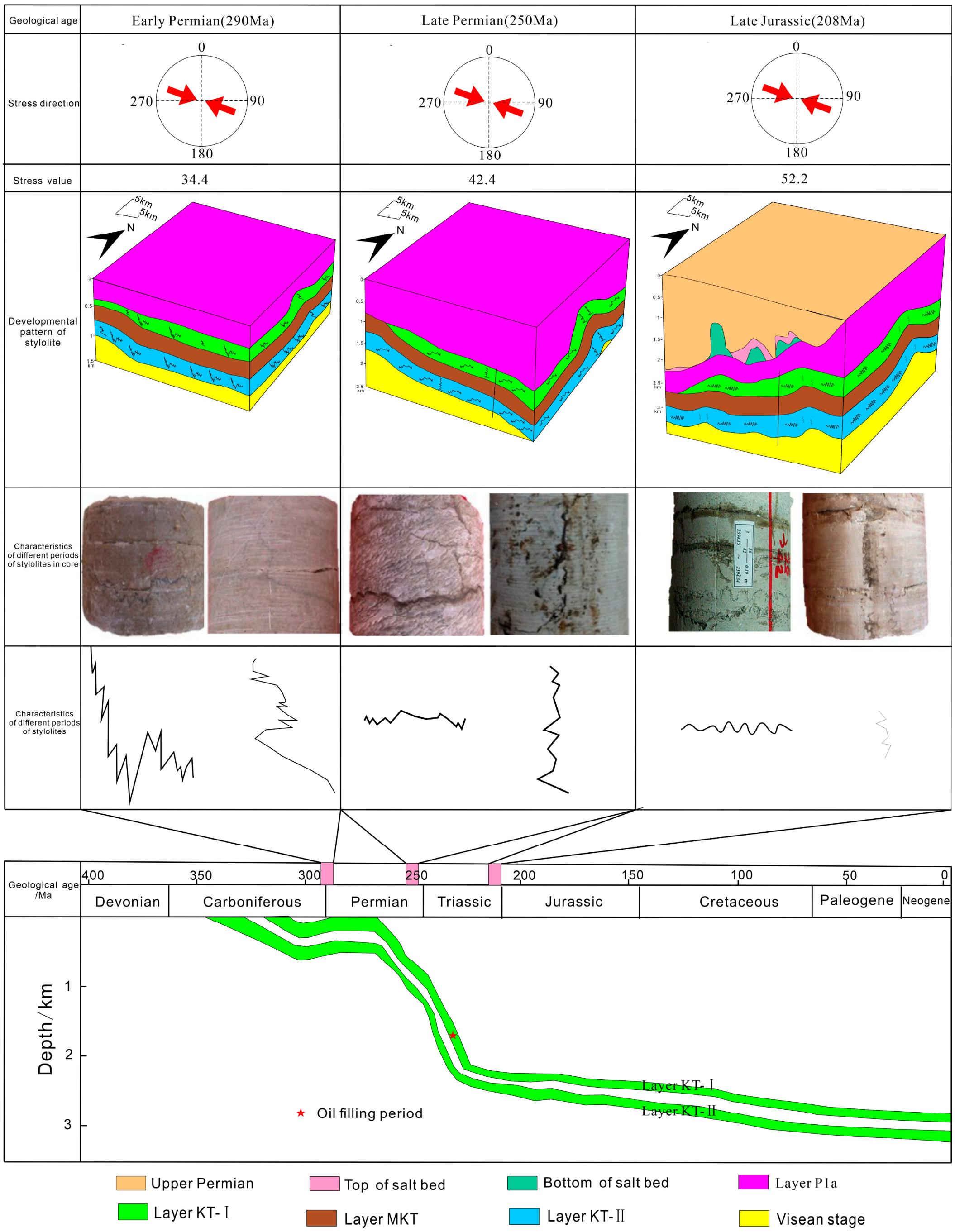

Figure 5. Evolution model of stylolites in the NT oilfield.

4.1.2. Analysis of Stylolites' Strike in Different Tectonic Movements

The strike of the stylolites in the study area was studied, based on the imaging logging data. It is difficult to accurately determine the cutting relationship and filling characteristics of stylolites based on the imaging logging data, due to the limited resolution, making it hard to analyze the stylolites' strike in different stages of the tectonic movements. However, the stress of the three periods of tectonic movement in the study area is all NW-SE tectonic compression, thus, the strike of the three periods of stylolites is the same [17]. The results show that the direction of the three periods of stylolites in the study area is mainly NE-SW trending, which is perpendicular to the direction of the maximum principal stress in the study area (Figure 6).

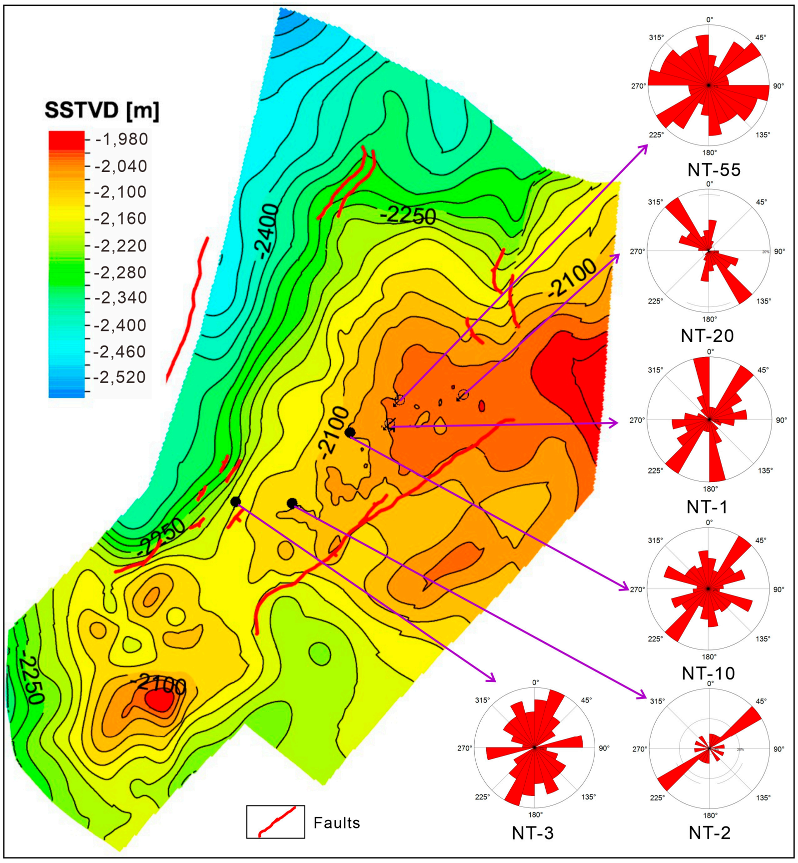

Figure 6. Strike of stylolites in the NT oilfield.

4.2. Analysis of Controlling Factors of Stylolites

Previous studies on the controlling factors of the stylolites primarily analyzed the influence of the present geological condition on the distribution of the stylolites [11,38,39], ignoring the difference between the present geological condition and the conditions at the time of the stylolites' formation. The geological conditions at the time of the stylolites' formation were studied, to further examine the controlling factors of the stylolites' development, in this paper. The development of stylolites is affected by the external stress and the features of rocks. The external stress can be evaluated by using the curvature and depth. The features of rocks include rock composition and rock texture, and the calcite content, dolomite content, and clay content can be used to evaluate the rock composition, and the rock texture can be evaluated by using the rock density, porosity, and grain size (r_5). Therefore, the controlling factors affecting the development of stylolites include structural location and depth, rock composition, porosity, density, and grain size (r_5).

4.2.1. Impacts of Structural Location and Depth on the Development of Stylolites

The formation of the low-angle bedding-parallel fractures in the study area is caused by the formation of the anticline, thus, the low-angle bedding-parallel fractures and the anticline were formed simultaneously. The low-angle bedding-parallel fractures were formed during the second period of tectonic movement [24], therefore the anticline in the study area was also formed during the second period of tectonic movement. Previous studies have shown that hydrocarbon emplacement in the study area was formed during the second period of tectonic movement [35–37], and hydrocarbon emplacement can only occur after the formation of the anticline. This indicates that hydrocarbon emplacement developed in a short time after the formation of the anticline in the study area, and therefore the geological structure at the time of hydrocarbon emplacement was the same as that during the formation of the second-period stylolites. The oil displaced the water in the reservoir, and it led to the stop of the pressure solution. Therefore, the oil-stained stylolites of the second period must be formed before hydrocarbon emplacement, and they developed simultaneously with the formation of the anticline. The oil reservoirs have been well preserved after formation, demonstrating that the anticline had nearly no change after oil charging, although it undergoes multi-period tectonic movements. Therefore, the anticline at the time of the formation of the second-period stylolites was the same as the present anticline. Besides, the reservoir was formed by oil displacement of the original reservoir fluid, and the reservoir now had a unified oil-water contact [40], it can be inferred that the reservoir fluid, before hydrocarbon emplacement in the study area, was connected in the reservoir. This demonstrates that the fluid properties in different structural locations of the anticline were the same at the time of the formation of the second-period stylolites. Therefore, the difference of fluid properties in the development of stylolites of the second period, can be ignored in this paper.

By analyzing the relationship between the distribution of the second-period stylolites and the structural location at the time of the formation of the second-period stylolites, the results show that both the low-angle and the high-angle stylolites developed more in the high part of the anticline (Figure 7). The minimum curvature of the structural surface was determined by using the Petrel software. The results show that the density of stylolites increases with the increase in the minimum curvature, further confirming that the stylolites are more developed in the high part of the anticline (Figure 8).

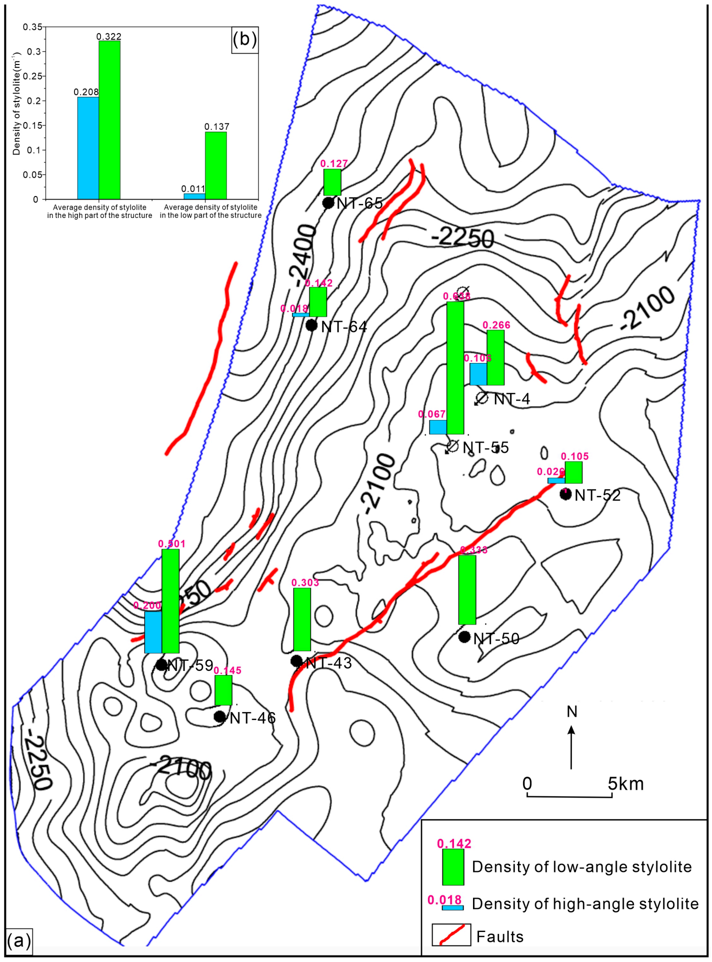

Figure 7. The distribution characteristics of the second-stage stylolites in the NT oilfield. (**a**) The planar distribution of the second-stage stylolites in the NT oilfield. (**b**) Comparison of the stylolites density in the high part and in the low part of the anticline.

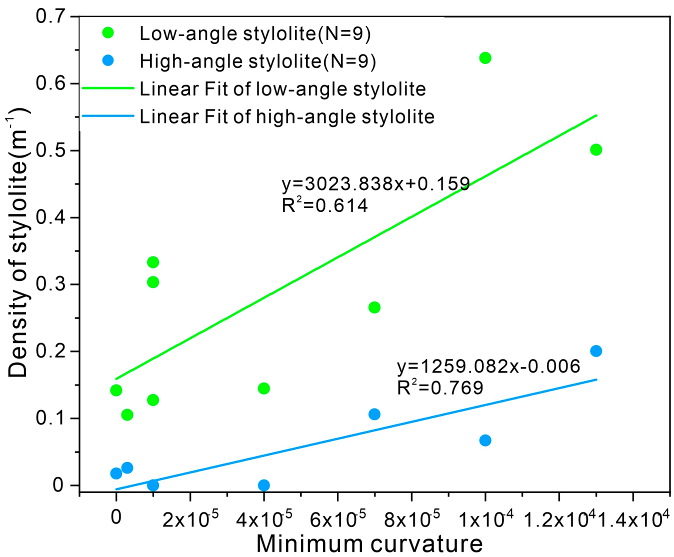

Figure 8. The relationship between minimum curvature and the density of stylolites.

There is a contradiction between the geological phenomenon, that the low-angle stylolites of the second period are easier to develop in the high part of the anticline, and the previously reported conclusion, that the low-angle stylolites are easier to develop in the low part of the anticline [9,41]. The influence of structural location on the development of low-angle stylolites is essentially the impact of depth. The deeper the buried depth is, the easier it is to develop stylolites (Figure 9). The buried depth of the lower part of the anticline is usually greater than that of the higher part, and the overburden pressure is larger, hence, it is easier to develop low-angle stylolites in the lower part of the anticline. To explain the geological phenomenon that the low-angle stylolites of the second period developed more easily in the high part of the anticline in the study area, the tectonic framework of the second period of tectonic movement was analyzed. The tectonic framework of the second period of tectonic movement is high in the west and low in the east, and the formation dip angle reached 15°. This illustrates that the crest of the anticline was deeper than the limbs when forming the second-period stylolites, and the low-angle stylolites of the second period are still more developed in the deeper zone (Figure 2), which is in agreement with the conclusions of previous work. The geological phenomenon that the low-angle stylolites of the second period developed more easily in the high part of the anticline in the study area, is caused by the paleotectonic framework. The high part of the anticline has greater horizontal compressive stress because of the larger tectonic deformation, thus it is easier for high-angle stylolites to form.

4.2.2. Implications of Rock Composition on the Development of Stylolites

Based on the log interpretation results of rock composition in the study area, the influence of rock compositions on the development of stylolites was investigated. In order to eliminate the influence of structural location and depth, this study selected the adjacent coring interval, with different rock composition for analysis. The results show that the dolomite of well section I (Figure 10a), is more developed than that of well section II (Figure 10a), but fewer stylolites developed in well section I. This indicates that the development of stylolites is inhibited with an increase in dolomite content, but it is promoted with an increase in limestone (Figure 10a). This is due to limestone being more prone to developing pressure solution than dolomite. Besides, well section I (Figure 10b) has a higher clay content than well section II (Figure 10b), and the stylolites are more developed in well section I, which indicates that the existence of clay can promote the development of stylolites.

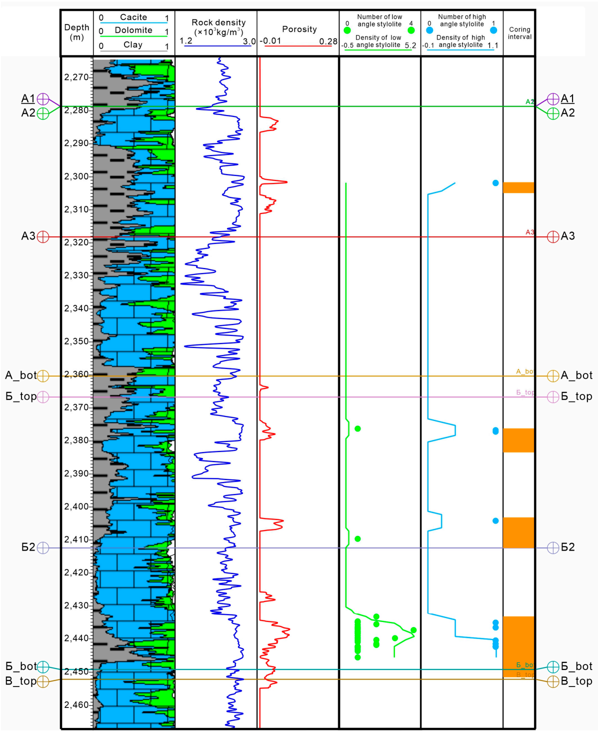

Figure 9. The intensity of stylolites at different depths of well N-52 in the NT oilfield.

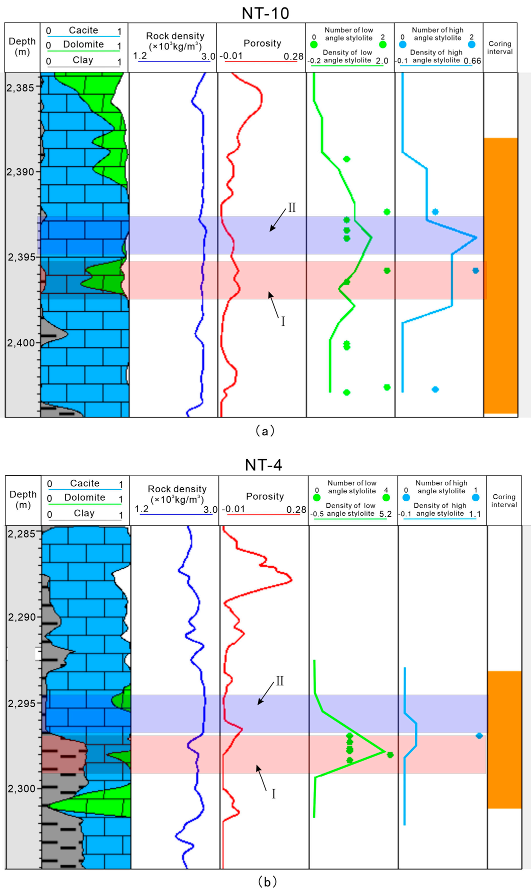

Figure 10. The intensity of stylolites in well intervals with different rock composition. (**a**) The interval with different rock composition of well NT-10. (**b**) The interval with different rock composition of well NT-4.

4.2.3. Effect of Rock Texture on the Development of Stylolites

(1) Influence of rock density and porosity on the development of stylolites

The impact of rock density on the development of stylolites was analyzed according to the rock density log and the linear density of stylolites. Rock density is mainly dictated by the mineral composition and porosity of the rock [42]. Therefore, in order to study the influence of rock density on the development of stylolites, it is necessary to first clarify the two important parameters of rock composition and rock porosity. The linear density of stylolites and rock porosity, shown in Figure 10a, are the average values of all sampling points within the corresponding variation range of rock density. Figure 10b displays the average mineral content of rock within the corresponding variation range of rock density. It can be seen in Figure 10a, that when the rock density is 2.4–2.5 $\times$ 10^3 kg/m^3 and 2.5–2.6 $\times$ 10^3 kg/m^3, the rock porosity is the largest, and the linear density of stylolites is also the largest. Therefore, with the increase in porosity, stylolites develop more easily in rocks. This is because the large porosity can make it easier for the fluid to flow, and promotes the continuous development of pressure solution.

In Figure 11a, the rock porosity is smaller when the rock density is 2.2–2.3 $\times$ 10^3 kg/m^3 and 2.3–2.4 $\times$ 10^3 kg/m^3, than that when the rock density is 2.6–2.7 $\times$ 10^3 kg/m^3 and 2.7–2.8 $\times$ 10^3 kg/m^3. Theoretically, the smaller the rock porosity is, the less developed the stylolites are. However, when the rock density is 2.2–2.3 $\times$ 10^3 kg/m^3 and 2.3–2.4 $\times$ 10^3 kg/m^3, the density of the stylolites is higher than that when it is 2.6–2.7 $\times$ 10^3 kg/m^3 and 2.7–2.8 $\times$ 10^3 kg/m^3, indicating that the smaller the rock density is, the more developed the stylolites are. According to Figure 11a,b, when the rock density is small, the clay content of the rock is high, which is consistent with the understanding that more stylolites develop with increasing clay content.

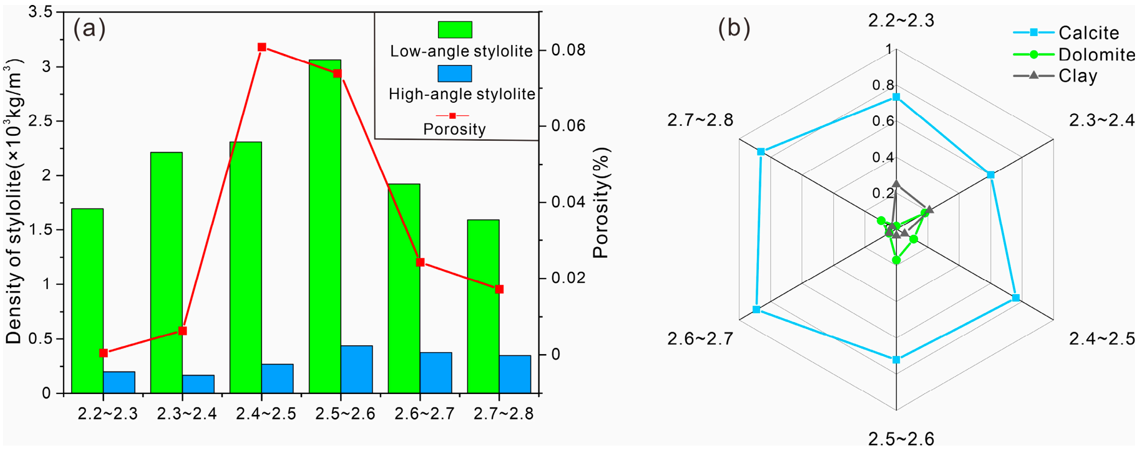

Figure 11. Influence of rock density on the development of stylolites. (**a**) The relationship between density of stylolites and rock density. (**b**) Rock composition of different rock density.

(2) Effect of grain size on the development of stylolites

Based on the data of mercury injection and the stylolites density log in the study area, the influence of rock grain size on the development of stylolites was researched. The results manifest that, although affected by other factors, the density of stylolites decreases with the increase in rock grain size (Figure 12). This is consistent with the previous experimental results of the effect of grain size on pressure solution [43]. This is mainly because the smaller the rock grain size, the larger the rock specific surface area, and the larger the contact area between rock and fluid, which is more conducive to accelerating the pressure solution rate.

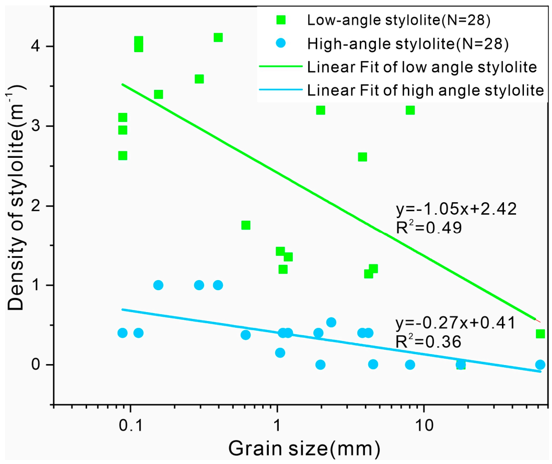

Figure 12. Relationship between grain size and density of stylolites.

5. Discussion

5.1. Comparation of the Influence of Different Controlling Factors on Stylolites Development

Based on the analysis of the influence of different factors on stylolites' development, this study further compared the influence of different controlling factors on stylolites' development by using grey relational analysis. The raw data are shown in Table 2.

Table 2. Raw data of density of stylolite and controlling factors.

Well	Curvature	Depth	Calcite Content	Dolomite Content	Clay Content	Rock Density	Porosity	r_5	Density of Low-Angle Stylolites	Density of High-Angle Stylolites
NT-55	0.000100	2309.3	0.283	0.267	0.45	2.308	0	62.114	0.39	0
NT-55	0.000100	2337.7	0.069	0.923	0.008	2.571	0.121	8.054	3.2	0
NT-55	0.000100	2338.9	0.073	0.920	0.007	2.558	0.126	1.976	3.2	0
NT-55	0.000100	2339.2	0.085	0.913	0.002	2.540	0.138	1.976	3.2	0
NT-55	0.000100	2347.8	0.354	0.474	0.172	2.444	0	17.808	0	0
NT-10	0.000118	2339.4	0.965	0	0.035	2.518	0.08	4.511	1.21	0.01
NT-10	0.000118	2340.3	0.991	0	0.009	2.603	0.05	1.048	1.43	0.15
NT-10	0.000118	2341.7	1	0	0	2.639	0.025	0.61	1.76	0.37
NT-10	0.000118	2342.6	0.999	0	0.001	2.673	0.028	1.188	1.36	0.4
NT-10	0.000118	2343.0	0.998	0.001	0.001	2.613	0.035	1.095	1.2	0.4
NT-10	0.000118	2344.0	0.848	0.147	0.005	2.486	0.149	4.187	1.14	0.4
NT-52	0.000003	2281.6	0.692	0.211	0.097	2.513	0.086	0.148	0	0.4
NT-52	0.000003	2281.7	0.718	0.176	0.106	2.574	0.067	0.148	0	0.39
NT-52	0.000003	2356.5	0.707	0.219	0.074	2.667	0.025	0.098	0.2	0.4
NT-52	0.000003	2414.6	0.945	0	0.055	2.462	0.031	0.089	2.63	0.4
NT-52	0.000003	2414.8	0.962	0	0.038	2.45	0.055	0.089	2.95	0.4
NT-52	0.000003	2414.9	0.964	0	0.036	2.449	0.061	0.089	3.11	0.4
NT-52	0.000003	2417	0.69	0.269	0.041	2.524	0.105	0.114	3.98	0.4
NT-52	0.000003	2417.2	0.645	0.323	0.032	2.537	0.1	0.114	4.07	0.4
NT-52	0.000003	2418.1	0.85	0.081	0.069	2.527	0.087	1.909	4.6	0.4
NT-52	0.000003	2418.2	0.846	0.087	0.067	2.524	0.088	1.909	4.62	0.4
NT-52	0.000003	2419.3	0.878	0.119	0.003	2.509	0.095	2.339	4.67	0.53
NT-52	0.000003	2420.3	0.857	0.108	0.035	2.58	0.061	0.396	4.11	1
NT-52	0.000003	2421.6	0.956	0	0.044	2.609	0.028	0.294	3.59	1
NT-52	0.000003	2422.2	0.722	0.278	0	2.589	0.055	0.155	3.4	1
NT-52	0.000003	2422.3	0.738	0.262	0	2.59	0.054	0.155	3.4	1
NT-52	0.000003	2422.5	0.747	0.237	0.016	2.624	0.044	0.155	3.4	1
NT-64	0	2598.2	0.976	0	0.024	2.635	0.018	3.803	2.62	0.4

The raw data were normalized, and the grey relational grade was calculated by applying the DPS software. The results illustrate that there are obvious differences in factors affecting the development of low-angle stylolites and high-angle stylolites. The importance of the influence of different controlling factors on the development of low-angle stylolites is given by depth, porosity, curvature, rock density, rock grain size, clay content, dolomite content, and calcite content, in this order. The importance of the influences on the development of high-angle stylolites proceeds as follows: curvature, calcite content, depth, rock grain size, clay content, rock density, dolomite content, and porosity (Table 3 and Figure 13). The low-angle stylolites are mainly affected by the depth, while the high-angle stylolites are primarily influenced by the structural location. The grey correlation analysis results show that the most critical controlling factor affecting the development of stylolites is tectonism. This is consistent with the general knowledge of the controlling factors for these two kinds of stylolites, and it confirms the accuracy of the analysis of the results.

Table 3. Results of grey correlation analysis.

Controlling Factors	Grey Relational Coefficient for High-Angle Stylolite	Ranking	Grey Relational Coefficient for Low-Angle Stylolite	Ranking
Curvature	0.8502	1	0.7955	3
Depth	0.8064	3	0.8783	1
Calcite content	0.8088	2	0.7524	8
Dolomite content	0.7679	7	0.7618	7
Clay content	0.7953	5	0.7627	6
Rock density	0.7740	6	0.7662	4
Porosity	0.7466	8	0.8034	2
r_5	0.8011	4	0.7650	5

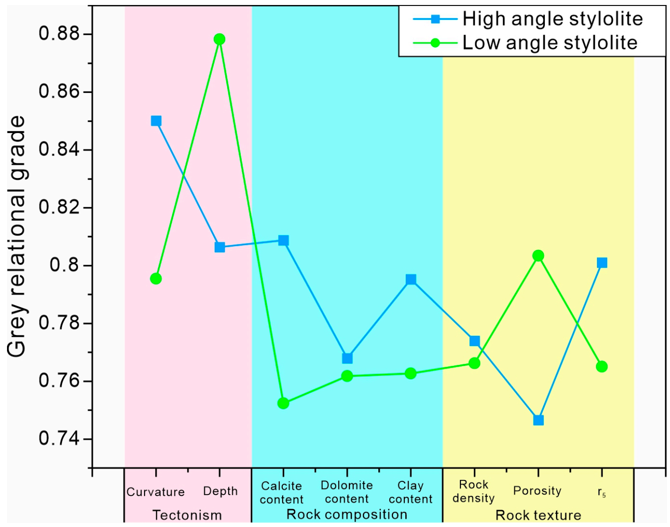

Figure 13. Analyzing the results of grey correlation analysis.

Porosity is one of the key controlling factors in the formation of low-angle stylolites, but it has little effect on the development of high-angle stylolites. High porosity of rocks can promote fluid flow and the pressure solution. The fluid in the formation flows horizontally, thus, the high porosity formation more easily develops low-angle stylolites. As for the high-angle stylolites, their longitudinal extension can pass through multiple layers. As long as there exists one layer with high porosity, the fluid can flow rapidly in the horizontal direction, and the pressure solution can develop continuously. The requirement for porosity for high-angle stylolites is lower than that for low-angle stylolites (Figure 14). Therefore, the influence of porosity on the development of high-angle stylolites is relatively small.

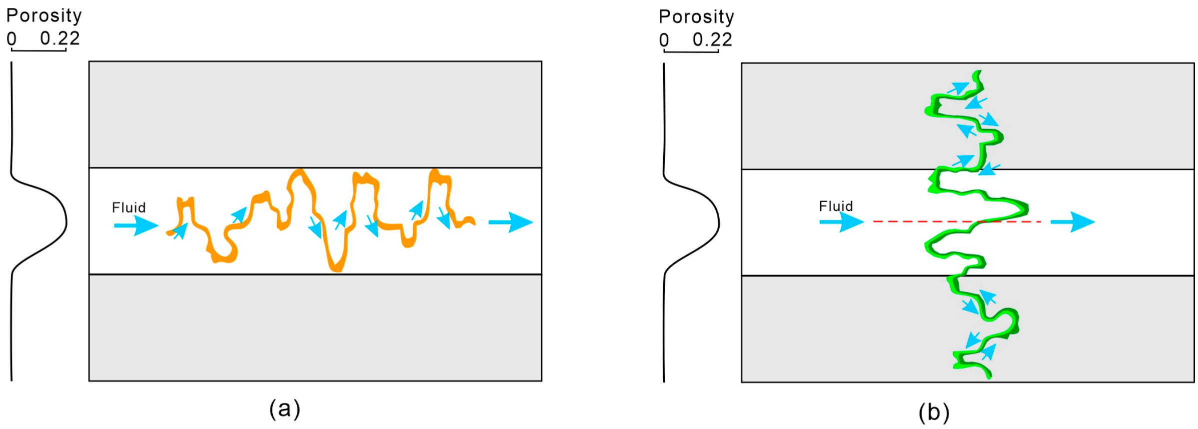

Figure 14. Effect of porosity on different dip angle stylolites. (**a**) Effect of porosity on low-angle stylolites. (**b**) Effect of porosity on high-angle stylolites.

5.2. Significance of Studying Stylolites for Oil and Gas Exploration and Development

Stylolites are of great significance for oil and gas exploration. Stylolites play an important role in hydrocarbon accumulation. First, stylolites are an important channel for oil and gas primary and secondary migration [44,45]. Second, stylolites are an important factor affecting oil and gas storage. Stylolites themselves can provide storage spaces for oil and gas, and can also affect the formation and distribution of caves in fractured-vuggy carbonate reservoirs [46].

Stylolites are also significant for oil and gas development. Stylolites can improve the permeability of the reservoir and promote seepage of underground oil and gas, which is an important factor affecting oil and gas productivity [46,47]. In addition, stylolites are of special importance to reservoir reconstruction, some of which can extend hundreds of meters, which is of great significance to improving the efficiency of reservoir reconstruction, for example, acid fracturing. However, it is also possible that stylolites connect with the edge water during the reservoir reconstruction process, which may induce water channeling. Therefore, it is necessary to evaluate the development characteristics of stylolites in the reservoir.

Because of the great importance of stylolites to oil and gas exploration and development, it is necessary to study the genesis and distribution of stylolites. However, previous studies ignored the issue of the formation period of stylolites, leading to some errors in the understanding of its genesis and the controlling factors of their distribution. This paper systematically elucidated the formation periods of stylolites in the NT oilfield, analyzed the controlling factors of stylolites, based on the stylolite of the second period, and compared the influence of different factors on stylolite development, which has important guiding significance for revealing the genesis and distribution of stylolites.

6. Conclusions

Based on the data from coring and imaging logging, the characteristics of stylolites in different periods were examined. There are three periods of stylolites, and all three periods developed both the low-angle stylolites and the high-angle stylolites in the study area. The prominent characteristics of both the low-angle and the high-angle stylolites of the second period are oil-stained. The three periods of stylolites in the study area are mainly NE-SW trending. Based on the interpretation results of the lithology log, porosity log, rock density log, mercury injection data, and stylolite density log, the controlling factors of the stylolites of the second period were analyzed. The development of stylolites is mainly affected by structural location, burial depth, rock composition, rock density, porosity and grain size. Both low-angle stylolites and high-angle stylolites are more prone to develop in the high parts of the anticline, the deep zone, zones with high content of limestone and clay, zones with low content of dolomite, and zones with low density, high porosity, and small grain size. The low-angle stylolites are more developed in the high part of the anticline due to the influence of the paleotectonic framework in the study area.

Based on grey correlation analysis, the influence of different controlling factors on the development of stylolites was analyzed. The importance of the influence of different controlling factors on the development of low-angle stylolites is given by depth, porosity, curvature, rock density, rock grain size, clay content, dolomite content, and calcite content, in this order. The importance of the influences on the development of high-angle stylolites proceeds as follows: curvature, calcite content, depth, rock grain size, clay content, rock density, dolomite content, and porosity. Tectonism is the most important factor affecting the development of stylolites.

Author Contributions: Conceptualization, C.L. and L.Z.; methodology, C.L.; software, W.L.; validation, W.Z., M.S. and Y.Z.; formal analysis, T.Z.; investigation, Y.Z.; resources, L.Z.; data curation, W.L.; writing—original draft preparation, C.L.; writing—review and editing, W.Z.; visualization, C.L.; supervision, L.Z.; project administration, L.Z.; funding acquisition, L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by China National Petroleum Corporation Science and Technology Program, grant number 2022DJ3210.

Data Availability Statement: Data available on request from the authors.

Acknowledgments: The authors would like to give special recognition to the China National Oil and Gas Exploration and Development Corporation for it provides the data for our research and we are grateful to the anonymous reviewers for their comments and very helpful suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Koehn, D.; Rood, M.P.; Beaudoin, N.; Chung, P.; Bons, P.D.; Gomez-Rivas, E. A new stylolite classification scheme to estimate compaction and local permeability variations. *Sediment. Geol.* **2016**, *346*, 60–71. [CrossRef]
2. Gomez-Rivas, E.; Martín-Martín, J.D.; Bons, P.D.; Koehn, D.; Griera, A.; Travé, A.; Llorens, M.G.; Humphrey, E.; Neilson, J. Stylolites and stylolite networks as primary controls on the geometry and distribution of carbonate diagenetic alterations. *Mar. Pet. Geol.* **2022**, *136*, 105444. [CrossRef]
3. Losonsky, G. Burial Depth and Lithofacies Control of Stylolite Development in the Mississippian Salem Limestone, Illinois Basin. Ph.D. Thesis, University of Cincinnati, Cincinnati, OH, USA, 1994.
4. Li, C.; Zhao, L.; Li, W.; Li, J.; Ding, Y.; Li, Y.; Qi, Y. Research status and its significance to oil-field development of stylolite in carbonate. *Nat. Gas Geosci.* **2019**, *30*, 493–502.
5. Li, C.; Zhao, L.; Liu, B.; Li, J.; Chen, Y.; Zhang, Y. Research status and development trend of fractures in carbonate reservoir. *Bull. Geol. Sci. Technol.* **2021**, *40*, 31–48.
6. Tada, R.; Siever, R. Pressure solution during diagenesis. *Annu. Rev. Earth Planet. Sci.* **1989**, *17*, 89. [CrossRef]
7. Rustichelli, A.; Tondi, E.; Korneva, I.; Korneva, I.; Baud, P.; Vinciguerra, S.; Agosta, F.; Reuschlé, T.; Janiseck, J. Bedding-parallel stylolites in shallow-water limestone successions of the Apulian Carbonate Platform (central-southern Italy). *Ital. J. Geosci.* **2015**, *134*, 513–534. [CrossRef]
8. Lind, I.L.; Berger, W.H.; Kroenke, L.W.; Mayer, L.A. Stylolites in chalk from leg 130, Ontong Java Plateau. In Proceedings of the Ocean Drilling Program, College Station, TX, USA, 18 January–26 March 1993.
9. Ehrenberg, S.N.; Morad, S.; Yaxin, L.; Chen, R. Stylolites and porosity in a Lower Cretaceous limestone reservoir, onshore Abu Dhabi, UAE. *J. Sediment. Res.* **2016**, *86*, 1228–1247. [CrossRef]
10. Hu, L.; Zou, H.; Yang, W.; Li, T.; Deng, C.; Cheng, Z.; Zhu, D.; Chen, X. Controlling factors of pressure dissolution of Cambrian carbonate in the northern Sichuan. *Geosci* **2022**, *3*, 1–14, (In Chinese with English abstract).
11. Yang, W.; Zou, H.; Li, T.; Hu, L.; Deng, C.; Cheng, Z.; Lan, C.; Xu, Z.; Chen, H.; Lu, C.; et al. Factors influencing stylolite formation in the Cambrian Longwangmiao Formation, Sichuan Basin, SW China. *J. Pet. Sci. Eng.* **2022**, *218*, 110946. [CrossRef]
12. Li, W.; Mu, L.; Zhao, L.; Li, J.; Wang, S.; Fan, Z.; Saho, D.; Li, C.; Shan, F.; Zhao, W.; et al. Pore-throat structure characteristics and its impact on the porosity and permeability relationship of Carboniferous carbonate reservoirs in eastern edge of Pre-Caspian Basin. *Pet. Explor. Dev.* **2020**, *47*, 958–971. [CrossRef]
13. Jackson, C.A.L.; Duffy, O.B.; Fernandez, N.; Dooley, T.P.; Hudec, M.R.; Jackson, M.P.; Burg, G. The stratigraphic record of minibasin subsidence, Precaspian Basin, Kazakhstan. *Basin Res.* **2020**, *32*, 739–763. [CrossRef]
14. Zeng, X.; Li, W.; Hou, J.; Zhao, W.; Liu, Y.; Kang, Y. Fractal Characteristics of Pore-Throats Structure and Quality Evaluation of Carbonate Reservoirs in Eastern Margin of Pre-Caspian Basin. *Energies* **2022**, *15*, 6357. [CrossRef]

15. Akhmetzhanov, A.; Zholtayev, G.; Djeddou, A.; Akhmetzhanova, G.; Oraz, B. Post-salt trapping mechanism of south-east Pre-Caspian and its application to petroleum exploration. *J. Pet. Explor. Prod. Technol.* **2020**, *10*, 2645–2653. [CrossRef]
16. Lu, J.; Tan, X.; Jin, Z.; Chen, Y.; Wang, S.; Zhao, W.; Li, C. Differential reservoir formation paths of carbonate rocks in early stage and impacts on reservoir properties: A case study of KT-I and KT-II layers in N Oilfield, Caspian Basin. *J. Palaeogeo.* **2022**, *25*, 1–19.
17. Li, C.; Zhao, L.; Li, J.; Wang, S.; Li, W. Structural fracture formation stages in the eastern margin of the Caspian Basin and genesis of low-angle structural fracture. *Spec. Oil Gas Reserv.* **2019**, *26*, 56–61.
18. Liang, S.; Wu, Y.; Wang, Y.; Wang, Z.; Sheng, S. Characteristics and principal controlling factors of sub-salt oil and gas accumulation in the eastern margin of the Precaspian Basin. *China Pet. Explor.* **2020**, *25*, 125.
19. Wu, Z.; Yin, H.; Wang, X.; Zhao, B.; Zheng, J.; Wang, X.; Wang, W. The structural styles and formation mechanism of salt structures in the Southern Precaspian Basin: Insights from seismic data and analog modeling. *Mar. Pet. Geol.* **2015**, *62*, 58–76. [CrossRef]
20. Sha, F.; Xiao, L.; Mao, Z.; Jia, C. Petrophysical characterization and fractal analysis of carbonate reservoirs of the eastern margin of the pre-Caspian Basin. *Energies* **2018**, *12*, 78. [CrossRef]
21. Zhang, S. *Geology of Sub-Salt Carbonate Rocks in the Rozhkovsky Structure, Northern Precaspian Basin, Kazakhstan: Implications for the Formation of Carbonate Reservoir in a Relatively Closed Diagenetic System*; The University of Regina: Regina, SK, Canada, 2021; pp. 1–213.
22. Chen, Z.; Sun, X.; Liu, L.; Guo, Z.; Ma, H.; Nie, G. Frequency-segmented inversion based on low-frequency seismic data in the central block of Pre-cas -pian Basin. *Oil Geophys. Prosp.* **2018**, *53*, 261–265.
23. Zhao, L.; Wang, S.Q.; Zhao, W.Q.; Luo, M.; Wang, C.G.; Cao, H.L.; He, L. Combination and distribution of reservoir space in complex carbonate rocks. *Pet. Sci.* **2016**, *13*, 450–462. [CrossRef]
24. Li, C.; Zhao, L.; Liu, B.; Liu, H.; Li, J.; Fan, Z.; Wang, J.; Li, W.; Zhao, W.; Sun, M. Origin, distribution and implications on production of bedding-parallel fractures: A case study from the Carboniferous KT-I Formation in the NT oilfield, Precaspian Basin, Kazakhstan. *J. Pet. Sci. Eng.* **2021**, *196*, 107655. [CrossRef]
25. Guo, K.; Cheng, X.; Fan, L.; Yan, S.; Ni, G.; Fu, H. Characteristics and development mechanism of dolomite reservoirs in North Truva of eastern Pre-Caspian Basin. *Acta Sedimentol. Sin.* **2016**, *34*, 747–757.
26. Xia, L.; Zhao, Y.; Yu, C.; Xi, K.; Ablimiti, Y.; Liu, H.; Chen, L. Key factors controlling deep Carboniferous volcanic reservoirs in the east slope of Mahu Sag, Junggar Basin, NW China. *J. Pet. Sci. Eng.* **2023**, *220*, 111223. [CrossRef]
27. Lang, X.L.; Guo, S.J. Fractured reservoir modeling method based on discrete fracture network model. *Acta Sci. Nat. Univ. Pekin.* **2013**, *49*, 964–972.
28. Roberts, A. Curvature attributes and their application to 3D interpreted horizons. *First Break.* **2001**, *19*, 85–100. [CrossRef]
29. Hu, X.; Hu, S.; Jin, F.; Huang, S. *Physics of Petroleum Reservoirs*; Springer: Berlin, Germany, 2017; pp. 1–506.
30. Zhou, H.; Guo, C.; Zhu, F. Application of Grey Relational Method in the Study of Shale Gas Resources Abundances Sensitivity. *Geol. Sci. Technol. Inf.* **2018**, *37*, 196.
31. Kuo, Y.; Yang, T.; Huang, G. The use of grey relational analysis in solving multiple attribute decision-making problems. *Comput. Ind. Eng.* **2008**, *55*, 80–93. [CrossRef]
32. Aman, B.A.; Nichols, T.W.; Snyder, R.L.; Payne, M.E. Integrated reservoir evaluation revives nearly abandoned Illinois Basin Field. In Proceedings of the SPE Eastern Regional Meeting, Charleston, WV, USA, 21 October 1999.
33. Park, W.; Schot, E.H. *Stylolitization in Carbonate Rocks*; Springer: Berlin, Germany, 1968; pp. 66–74.
34. Köehn, D.; Köehler, S.; Toussaint, R.; Ghani, I.; Stollhofen, H. Scaling analysis, correlation length and compaction estimates of natural and simulated stylolites. *J. Struct. Geol.* **2022**, *161*, 104670. [CrossRef]
35. He, D. *Evaluation of Conventional Hydrocarbon Resources in Sedimentary Basins of Central Asia Region*; Science Press: Beijing, China, 2016; pp. 1–330.
36. Tian, N.; Yan, S.; Hui, G. Controlling factors of petroleum accumulation in pre-salt strata in south uplift of PreCaspian Basin. *Xinjiang Pet. Geol.* **2015**, *36*, 116.
37. Zhu, S.; Li, J.; Chen, H.; Hu, Y.; Yang, F.; Xu, X. Hydrocarbon accumulation condition and main controlling factors of sub-salt strata in southern uplift of Pre-Caspian basin. *Pet. Geol. Eng.* **2018**, *32*, 28–32.
38. Humphrey, E.; Gomez-Rivas, E.; Neilson, J.; Martín-Martín, J.D.; Healy, D.; Yao, S.; Bons, P.D. Quantitative analysis of stylolite networks in different platform carbonate facies. *Mar. Pet. Geol.* **2020**, *114*, 104203. [CrossRef]
39. Zhou, L.; Wang, G.; Hao, F.; Xu, R.; Jin, Z.; Quan, L.; Zou, H. The quantitative characterization of stylolites in the limestone reservoirs of the Lower Triassic Feixianguan Formation, northeastern Sichuan Basin: Insights to the influence of pressure solution on the quality of carbonate reservoirs. *Mar. Pet. Geol.* **2022**, *139*, 105612. [CrossRef]
40. Di, W. Study on Technical Measures for Development of the North Tluwa Carbonate Reservoirs. Ph.D. Thesis, China University of Petroleum (Beijing), Beijing, China, 2018.
41. Peacock, D.; Azzam, I.N. Development and scaling relationships of a stylolite population. *J. Struct. Geol.* **2006**, *28*, 1883–1889. [CrossRef]
42. Xiang, L. The Application of Integrated Geophysical and Geochemical Methods in Mineral Prospecting in Jirigen Forest Area. Ph.D. Thesis, Jilin University, Changchun, China, 2018.
43. Zhang, X.; Spiers, C.J. Compaction of granular calcite by pressure solution at room temperature and effects of pore fluid chemistry. *Int. J. Rock. Mech. Min.* **2005**, *42*, 950–960. [CrossRef]

44. Zhu, K.; Gao, G.; Liu, S.; Wang, C.; Cheng, J.; Hu, D. Origin of Organic Matter, Fluid Transport and Geological Significance in Stylolites. *Acta Sedimentol. Sin.* **2023**, *4*, 1–19.
45. Liu, S.; Gao, G.; Gang, W.; Qu, T.; Dang, W.; Zhang, W.; Yang, S.; Zhu, K. Implications of organic matter source and fluid migration from geochemical characteristics of stylolites and matrix in carbonate rocks: A case study from the Carboniferous and the Ordovician in the Sichuan Basin, SW China. *J. Pet. Sci. Eng.* **2020**, *186*, 106606. [CrossRef]
46. Pontes, C.C.; Balsamo, F.; Pizzati, M.; Bezerra, F.H.; La Bruna, V.; Lima, R.S. Burial stylolites enhance karst dissolution and control cave geometry in heterolithic carbonates, Salitre Formation, Brazil. *Mar. Pet. Geol.* **2023**, *148*, b106029. [CrossRef]
47. Bruna, P.O.; Lavenu, A.P.; Matonti, C.; Bertotti, G. Are stylolites fluid-flow efficient features. *J. Struct. Geol.* **2019**, *125*, 270–277. [CrossRef]