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*Research Article*

# Sedimentary Characteristics and Evolution Controlling Factors of Platform Margin Reef-Shoal: A Case Study of Upper Carboniferous-Middle Permian in Wushi Area, Tarim Basin

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Upper Carboniferous-Middle Permian platform margin reef-shoal reservoirs are one of the most important exploration targets for the northwestern margin of Tarim Basin. In order to obtain a clear understanding of the controlling factors for the platform margin reef-shoal development, field outcrops in the Wushi area, northwestern margin of Tarim Basin had been studied in this article by field measurements, thin section identification, carbon and oxygen isotope testing, and ancient provenance analysis. Studies have shown that the platform margin reefs in the Wushi area were dominated by algae reefs, and the platform margin shoals are dominated by bioclastic shoals and gravel shoals. The characteristics of algal bind inside grains were common. During the Zhaerjiake period, interbedded reefs and shoals were the main type, and platform marginal reefs were of the progressive type. During the Balediertage period, huge thick platform margin reefs were the main type, and the platform margin reefs were of accretion-weak progressive type. The development controlling factors of the platform margin reef-shoal are mainly relative sea-level change, palaeosource, and paleogeomorphy. Relative sea-level changes controlled the development characteristics and superposition mode of the platform margin reef-shoal; there were two sides of the influence of the palaeosource on the platform margin reef-shoal; the paleogeomorphology controlled the development position and spreading scale of platform margin reef-shoal. In the covering area, the platform margin reef-shoal reservoirs adjacent to the fault zone and with large sedimentary thickness might have a good prospect for hydrocarbon exploration.

## 1. Introduction

Reef-shoal reservoirs play an important role in carbonate reservoirs and are prone to form high-yield oil and gas fields with huge reserves, such as Ghawar oil field in Saudi Arabia, Zertan oil field in Libya, and Old Golden Lane oil field in Mexico [1]. In recent years, with major breakthroughs in reef-shoal facies oil and gas fields of Upper Ordovician Lianglitage Formation in Tarim Basin, Triassic Changxing Formation, and Feixianguan Formation in Sichuan Basin, such as Tazhong I gas field, Puguang gas field, and Yuanba gas field, the research interest of reef-shoal facies is increasing [2–6]. Studies show that the favorable area of reef-shoal body in Tarim Basin is $1.58 \times 104\,km^2$, and the amount of oil and gas resources is more than $1.5 \times 109\,t$, indicating its huge exploration potential [7]. As one of the important exploration targets in Tarim Basin, the Carboniferous-Permian reef-shoal reservoirs have been found in Tazhong area (Tahe 1 well and Tazhong 4 well) [8]. However, in the northwestern margin of Tarim Basin, the Carboniferous-Permian is buried deeply in the covering area, and no exploration wells have been drilled into the target layer. Therefore, field outcrop research of platform margin reef facies is of great significance for hydrocarbon exploration. Many previous studies have been carried out on the platform margin reef-shoal facies of the Carboniferous-Permian in the northwestern margin of Tarim Basin. Based on the outcrop research in Keping area, Zhang believed that the platform margin reef-shoal in the northwestern margin of Tarim was mainly developed in Late Carboniferous to Early

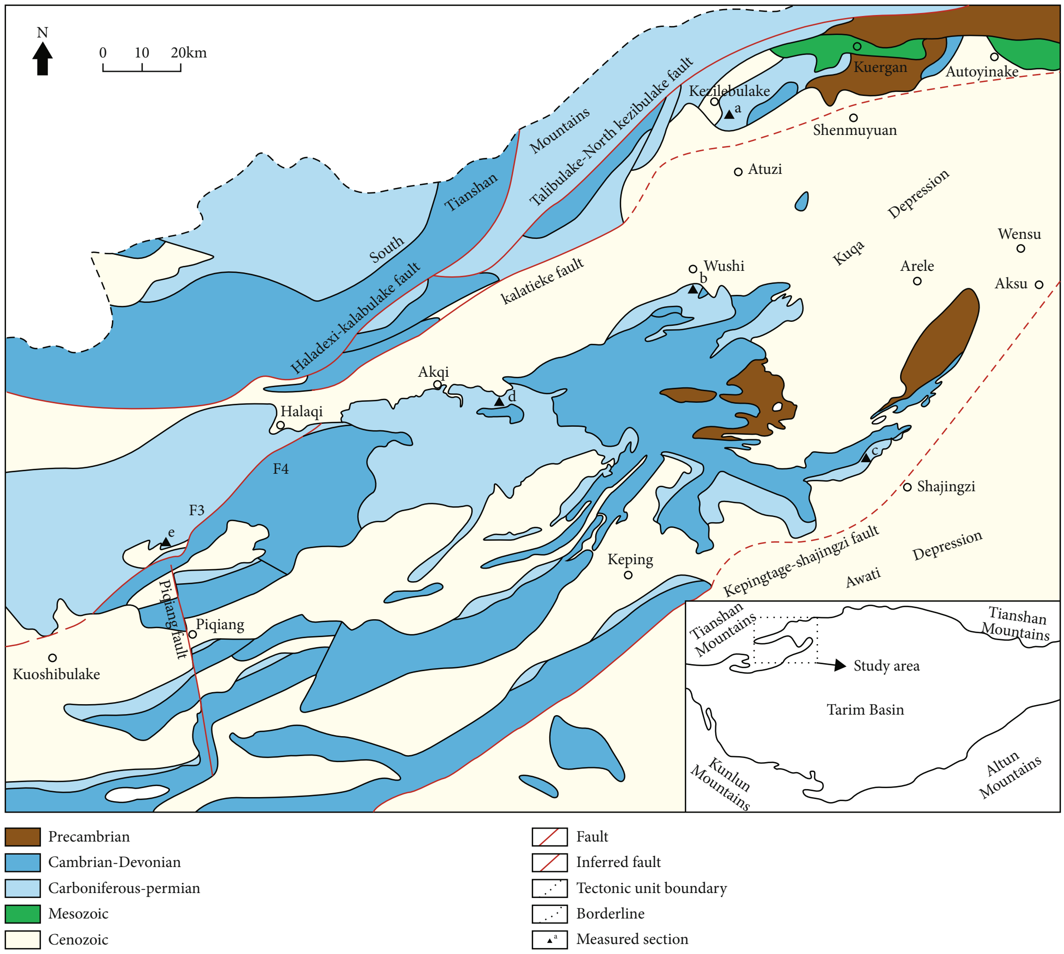
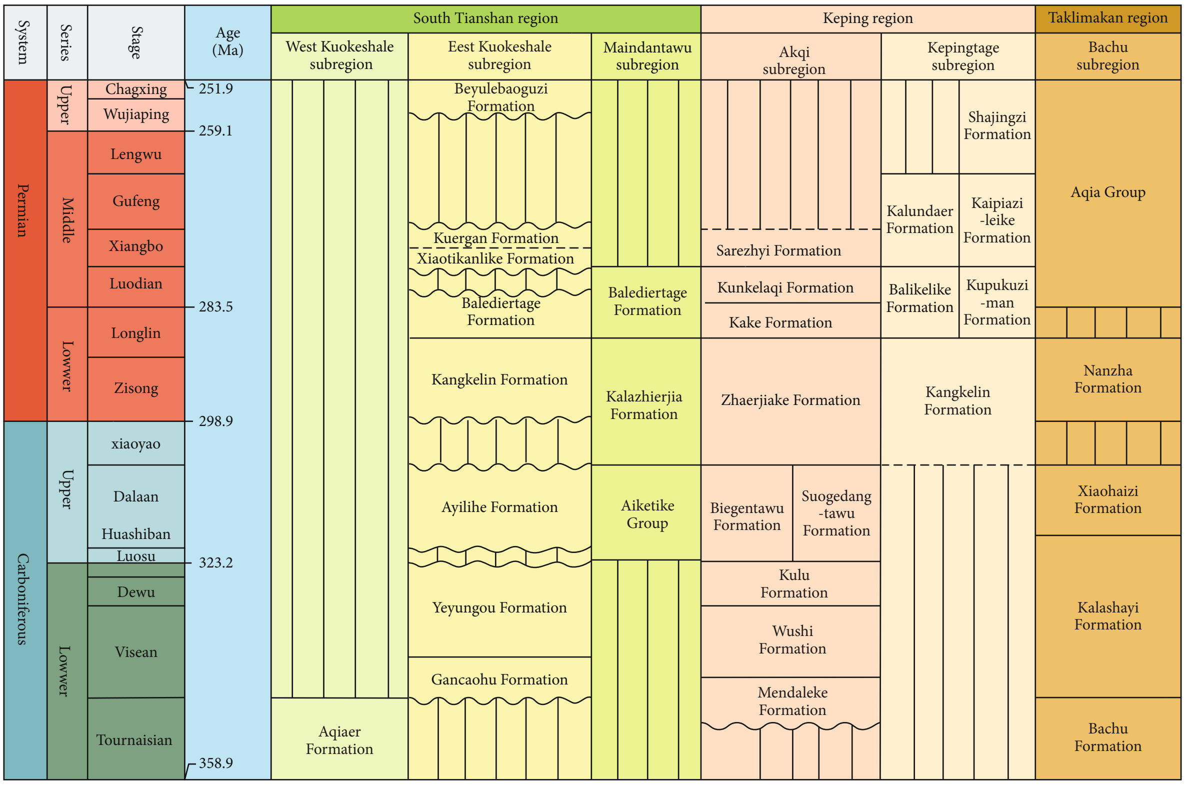



Figure 1: Location and stratigraphic distribution in Wushi area, northwestern of Tarim Basin. (a) Kezilebulake. (b) South of Wushi. (c) Sishichang. (d) Sepabayi. (e) Aoyibulake.

Permian, and the reef-building organisms were mainly blue-green algae [9]. Deledaer further studies suggested that the stable transgression of Late Carboniferous to Early Permian was the basis for the large-scale development of carbonate platforms and platform margin reef-shoals [10]. Based on the study of Kangkelin Formation in the Western Tarim Basin, Wang proposed that sea-level fluctuation and palaeotopography controlled the migration of reef-shoals, and the sedimentary background of platform margin reef-shoal was carbonate gentle slope model [8]. Through a systematic study of Permian reef limestone in the northwestern margin of Tarim Basin, Luo believed that the progradational reef with huge thickness reflected that the growth rate of reef body matched the rate of reef base [11]. It can be seen that researchers have studied the sedimentary characteristics, spatial and temporal distribution, migration mechanism, and sedimentary model of platform margin reef-shoals [8–11], but the sedimentary differences and controlling factors of platform margin reef bank in different periods and tectonic positions are not discussed. This problem affects the understanding and exploration evaluation of platform margin reef-shoal facies development law. Taking the upper Carboniferous-Middle Permian in Wushi area as an example, this paper systematically studies the large sedimentary differences of the platform margin reef-shoal in different periods and different tectonic positions. On this basis, the evolution controlling factors and exploration potential of platform margin reef-shoal in are discussed, via stable isotope test, Fluorescent thin section observation, reservoir porosity, and permeability test. The research results of this paper can provide reference for the hydrocarbon exploration of platform margin reef-shoal in Tarim Basin.

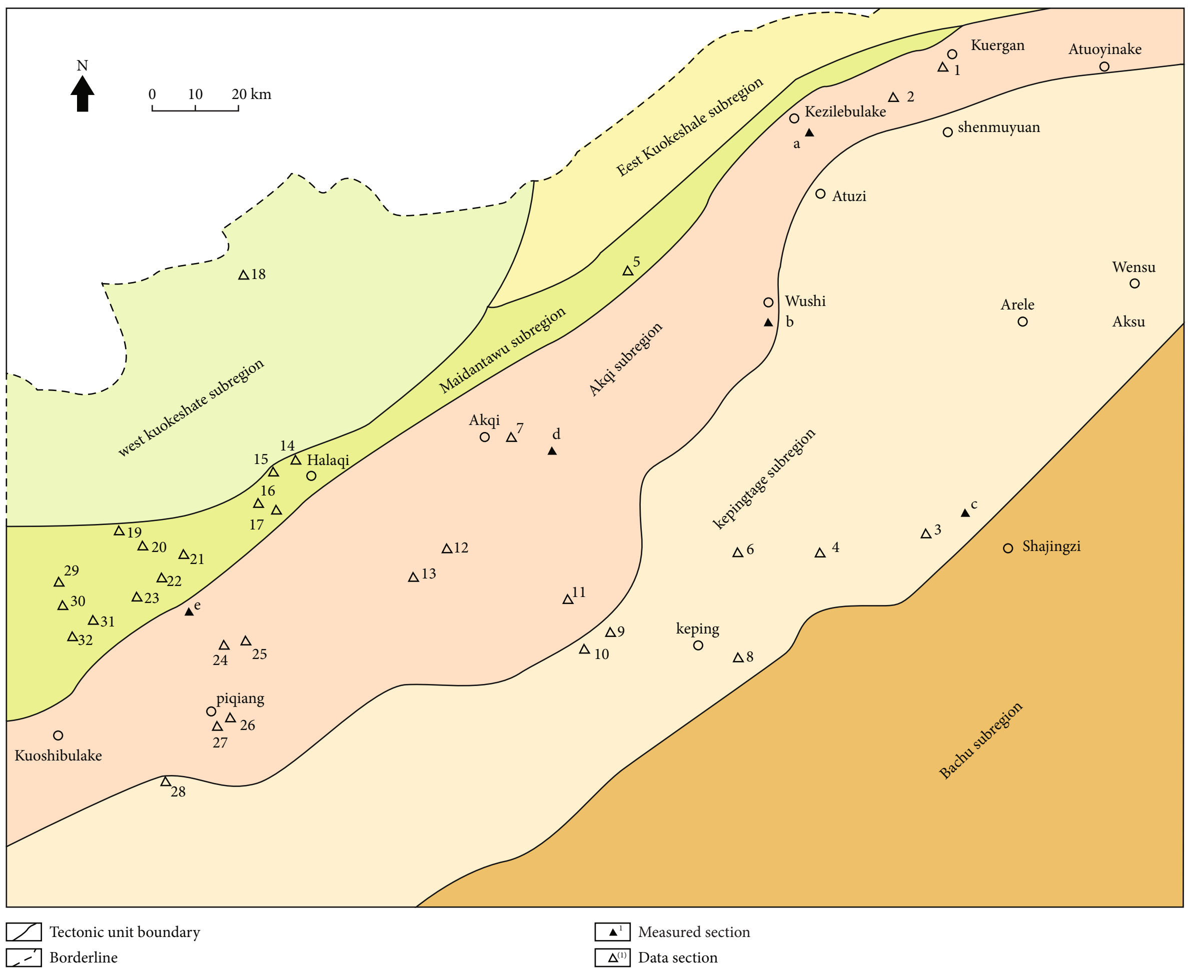
## 2. Geology Settings

Wushi area is located in the northwest margin of Tarim Basin, connected with the southern Tianshan orogenic belt by the Kalatieke fault to the north, and connected with the Awati Depression and Bachu Uplift by the Kepingtage-Shajingzi fault to the south, and connected with Aksu area in the east and Piqiang area in the west (Figure 1). Tectonically, Wushi area is located between Tarim block and southern Tianshan orogenic belt. Since the Late Devonian, the Yili-Central Tianshan Block first collided with the eastern Tarim Block. In the Carboniferous, southern Tianshan ocean closed from east to west in a scisscis-type manner until the southern Tianshan ocean closed [12]. From Late Carboniferous to Early Middle Permian, the northwestern




(a)

Figure 2: Continued.




(b)

Figure 2: Stratigraphic division and regionalization scheme of Carboniferous-Permian in Wushi area, northwestern of Tarim Basin. (a) Kezilebulake. (b) South of Wushi. (c) Sishichang. (d) Sepabayi. (e) Aoyibulake. (1) Kuergan; (2) Shenmuyuan; (3) Kaipaiziruike; (4) south slope of Yinganshan; (5) Kekeyumusu; (6) Tongguzibu; (7) north bridge of Tuoshihan; (8) Xiaoerbulake; (9) Subashi-I; (10) Subashi-II; (11)Tikeliketage-Qiudayisayi; (12) Kake; (13) Muziduke; (14) Halaqi-I; (15) Halaqi-II; (16) Bijingtawu-I; (17) Bijingtawu-II; (18) Keleikesu river valley; (19) north slope of Kalatieke Mountain-I; (20) north slope of Kalatieke Mountain-II; (21)Yiqike; (22) south foothills of Kalatieke-I Yimugantawu; (23) Huoshibulake; (24) Kekebukesan Mountain-I; (25) Kekebukesan Mountain-II; (26) west of Piqiang Mountain; (27) Kekebukesan Mountain-III; (28) Yimugantawu; (29) Kutiereke-I; (30) Kutiereke-II; (31) foothill of Kalatieke Mountain-II; and (32) Kutiereke-III.

margin of Tarim Basin did not build mountains strongly immediately after the closure of the southern Tianshan ocean basin, but still developed a foreland remnant basin opening westward [13, 14]. The platform margin reef-shoal in Wushi area was developed in this tectonic background. After the Middle Permian, the late Tianshan movement led the revival of the southern Tianshan orogenic belt, and the strong compressional nappe closed the residual basin. The Wushi area started the molasite evolution stage of the foreland basin. After that, Yanshanian, Indosinian, and Himalayan movement caused multiple thrust nappe and strike-slip, which further complicated the distribution of Carboniferous-Permian in Wushi area.

Because the distribution of Carboniferous-Permian in Wushi, Keping, and Aheqi is relatively stable (Figure 1), a systematic stratigraphic framework has been established [15, 16]. Wushi area can be divided into 3 stratigraphic regions and 6 stratigraphic subregions (Figure 2). According to section, the platform reef-shoal facies was mainly developed during Late Carboniferous-Middle Permian in Kepingtag, Aheqi, and Maidantawu stratigraphic regions. Kangkelin Formation (($C_2$-$P_1$) *k*), Zarjake Formation (($C_2$-$P_1$) *z*), Kalazhierjia Formation (($C_2$-$P_1$) *kl*), Balediertage Formation ($P_{1\text{-}2}b$), and Kunkelaqi Formation ($P_{1\text{-}2}k$) were involved (Figure 2(a)). In order to facilitate understanding, Zhaerjiake period and Balediertage period are adopted in the following paper when the sedimentary characteristics of platform margin reef-shoal in different periods are described.

## 3. Materials and Methods

*3.1. Materials.* The samples in this study are from 5 Carboniferous-Permian sections (section a–e) in Wushi

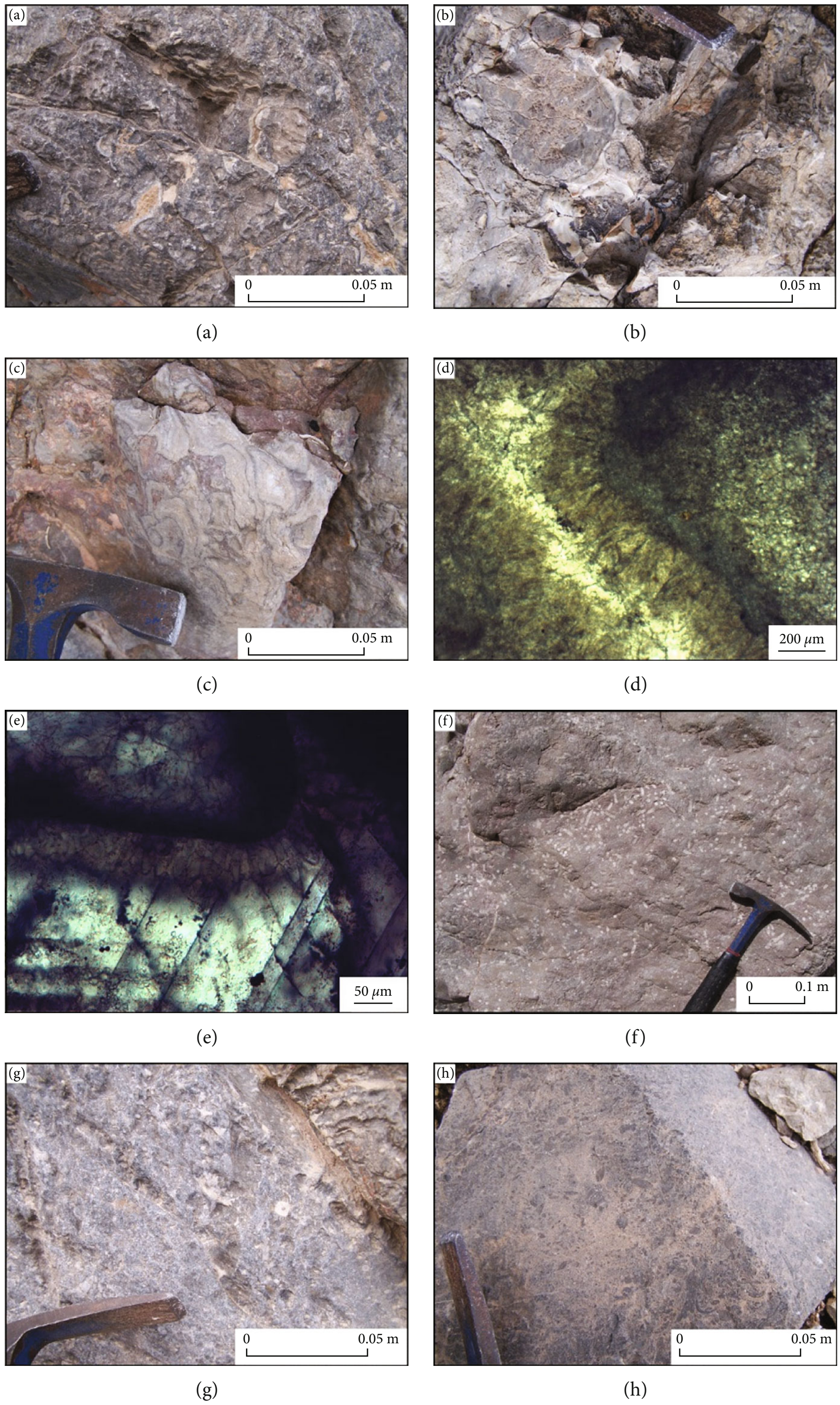



FIGURE 3: Continued.

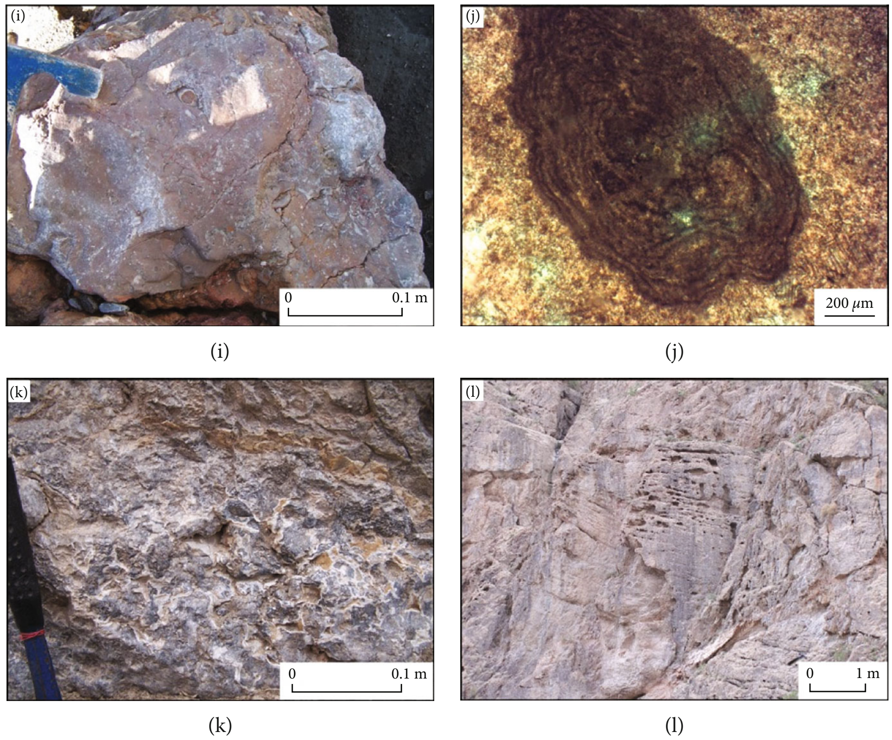



Figure 3: Outcrops and microscope photos of platform margin reef-shoal facies in Wushi region. (a) Algal bonded reef limestone, Zhaerjiake Formation, section e. (b) Algal bonded reef limestone, Kunkelaqi Formation, section d. (c) Algal bonded reef limestone, Balediertage Formation, section a. (d) Bonding layer in algal bonded reef limestone, Kunkelaqi Formation, section e. (e) Two stage carbonate filler in algal bonded reef limestone, Balediertage Formation, section a. (f) Crinoid micrite limestone, Balediertage Formation, section a. (g) Bioclastic micritic limestone, Zhaerjiake Formation, section e. (h) Bioclastic limestone, Zhaerjiake Formation, section d. (i) Bioclastic micrite limestone, Balediertage Formation, section a. (j) Algal clast micrite limestone, Kunkelaqi Formation, section e. (k) Algal bonded calcirudite, Zhaerjiake Formation, section e. (l) Bioclastic gravel-bearing arenaceous limestone, Balerdiertage Formation, section a.

area, northwestern of Tarim Basin (Figure 1). Based on detailed field outcrops observation, 171 rock samples were collected in total. Through hand specimens and microscopic observation, 33 samples were used for stable isotope analysis, 18 samples were used for reservoir porosity and permeability test, and 3 samples were used for fluorescent thin section observation.

### 3.2. Experimental Method

*3.2.1. C and O Isotope Analysis.* The C and O isotopic content of seawater varies with the sedimentary environment, and these changes are recorded in syn-sedimentary carbonate rocks. C and O isotope content has been widely used to study regional and global relative sea-level change [17–20]. C and O isotope analysis of carbonate rocks mainly adopts phosphoric acid method which is widely used by laboratories. The experimental method is that carbonate minerals react with 100% phosphoric acid at a specific temperature to release $CO_2$, and the C and O isotope content of carbonate can be determined by measuring the C and O isotope of $CO_2$.

The detailed experimental process is as follows. (1) Under the condition of high vacuum, the carbonate rock sample is subjected to constant temperature reaction with 100% phosphoric acid, in which the limestone part is fully reacted at $(25.0 \pm 0.1)^{\circ}C$ for 24 hours, and the dolomitic part fully reacts at $(50.0^{\circ}C \pm 0.1)$ for 72 hours. (2) The generated water is separated by freezing method to collect $CO_2$, and then, the $CO_2$ is sent to the stable isotope mass spectrometer (MAT-252) for obtaining C and O isotope content.

In order to facilitate the comparison with other C and O isotope test results, the test results are expressed by the thousandth difference of the isotope ratio between the test value and the standard sample (Pee Dee Belemnite) value, $\delta^{13}C_{PDB}$, and $\delta^{18}O_{PDB}$.

*3.2.2. Reservoir Porosity and Permeability Test.* Helium gas is an inert gas, not easy for chemical reaction, and can effectively inhibit the gas effect. Using helium gas as the test medium not only does not pollute the sample, but also ensures high test accuracy. Therefore, helium gas is used as the medium in this experiment. POROPDP-200 apparatus is used to test the porosity and permeability of the sample.

Reservoir porosity test consists of four steps. (1) Set the temperature to $200 \pm 2^{\circ}C$, and put the sample into the constant temperature drying oven until completely drying (test dry weight less than 0.001 g); (2) after cooling to room temperature, the samples were loaded into the sample chamber, and the pressure in the standard chamber filled with gas and equilibrium state was recorded, respectively; (3) the rock skeleton volume can be calculated according to Boyle's law,

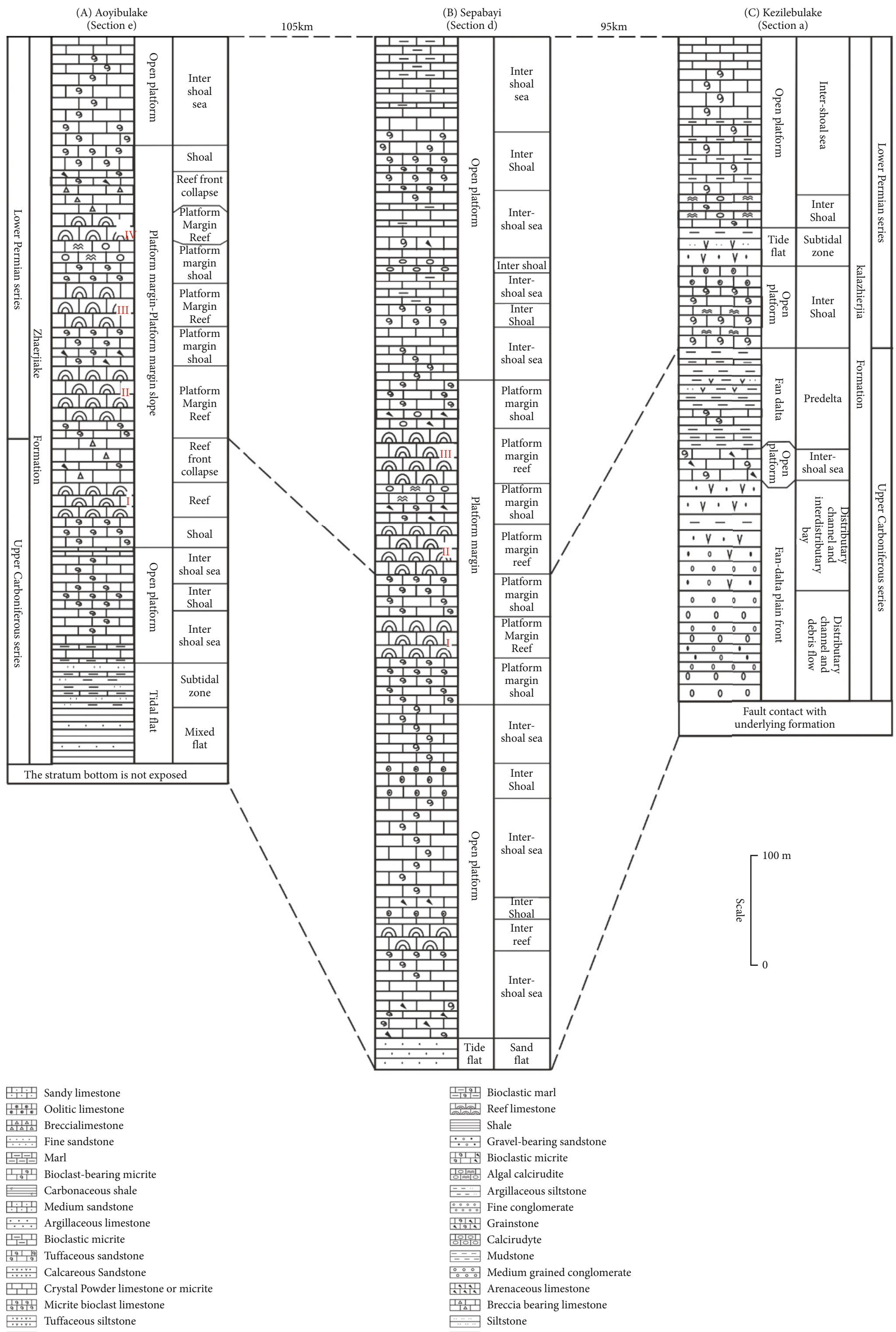


Figure 4: Stratigraphic histogram of Zhaerjiake period in Wushi region, northwestern of Tarim Basin.

and the total volume of rock can be measured by powder accumulation method; and (4) calculate the sample porosity.

Reservoir permeability test consists of three steps. (1) Set the temperature to $200 \pm 2^{\circ}C$, and put the sample into the constant temperature drying oven until completely dried (test dry weight less than 0.001 g); (2) after cooling to room temperature, the samples are loaded into the sample chamber; (3) increase the confining pressure, pass the gas to test the flow rate, and record the gas flow rate through the sample per unit time and the pressure value above and below the sample; and (4) calculate the sample permeability.

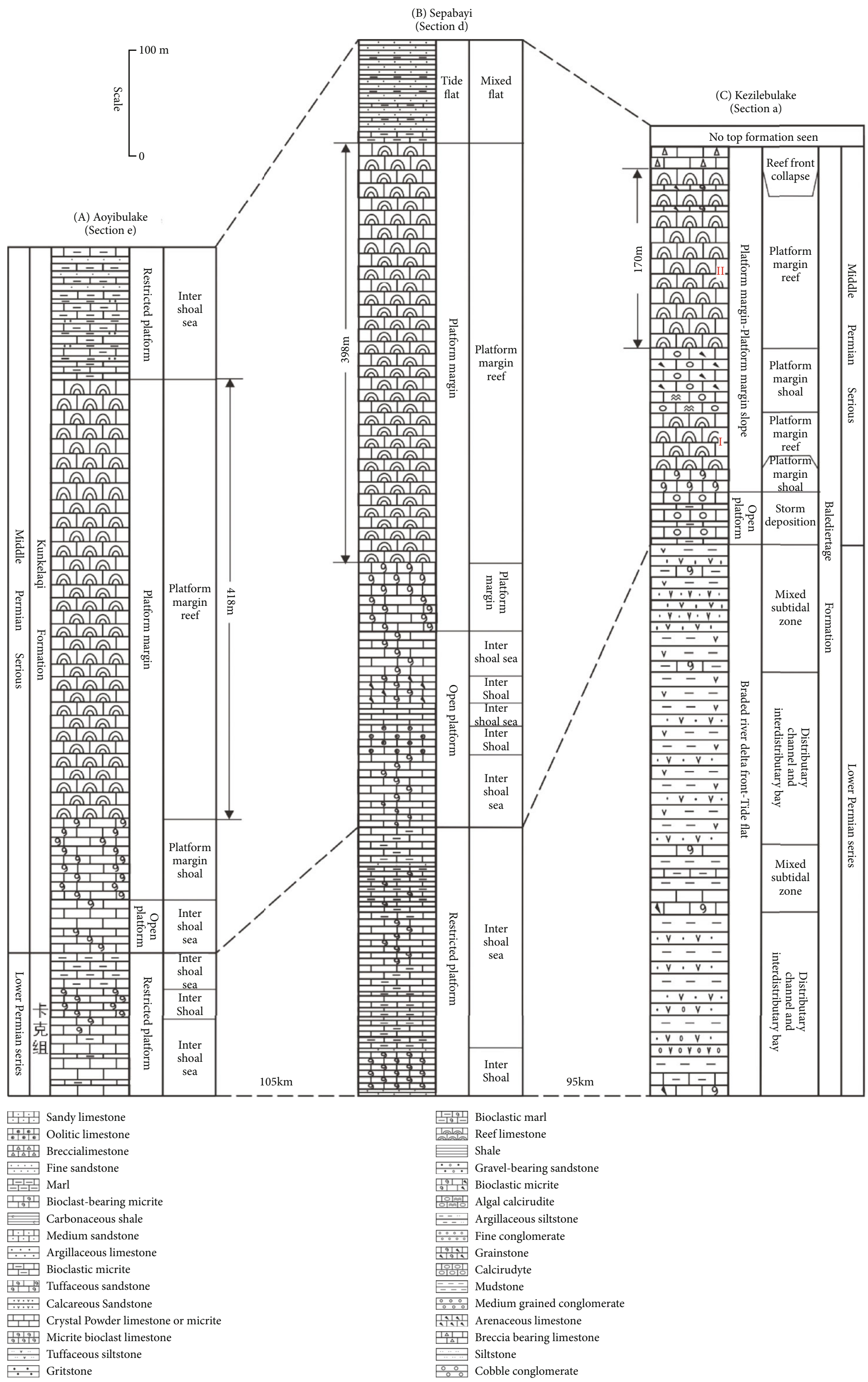



FIGURE 5: Stratigraphic histogram of Balediertage period in Wushi area, northwestern of Tarim Basin.

*3.2.3. Fluorescent Thin Section Observation.* Hydrocarbons and other organic matter contents in rocks glow in different colors under UV excitation. With the increase of the maturity of petroleum components, the fluorescence wavelength will shorten. Therefore, hydrocarbon properties can be inferred by fluorescence color and luminance.

ORTHOLUX-II fluorescence microscope is used in this experiment; the experimental process is as follows: (1) through the thin section observation, the suitable carbonate samples for fluorescent examination should be selected; (2) make the selected samples into fluorescent thin section; and (3) through the fluorescent thin section observation,

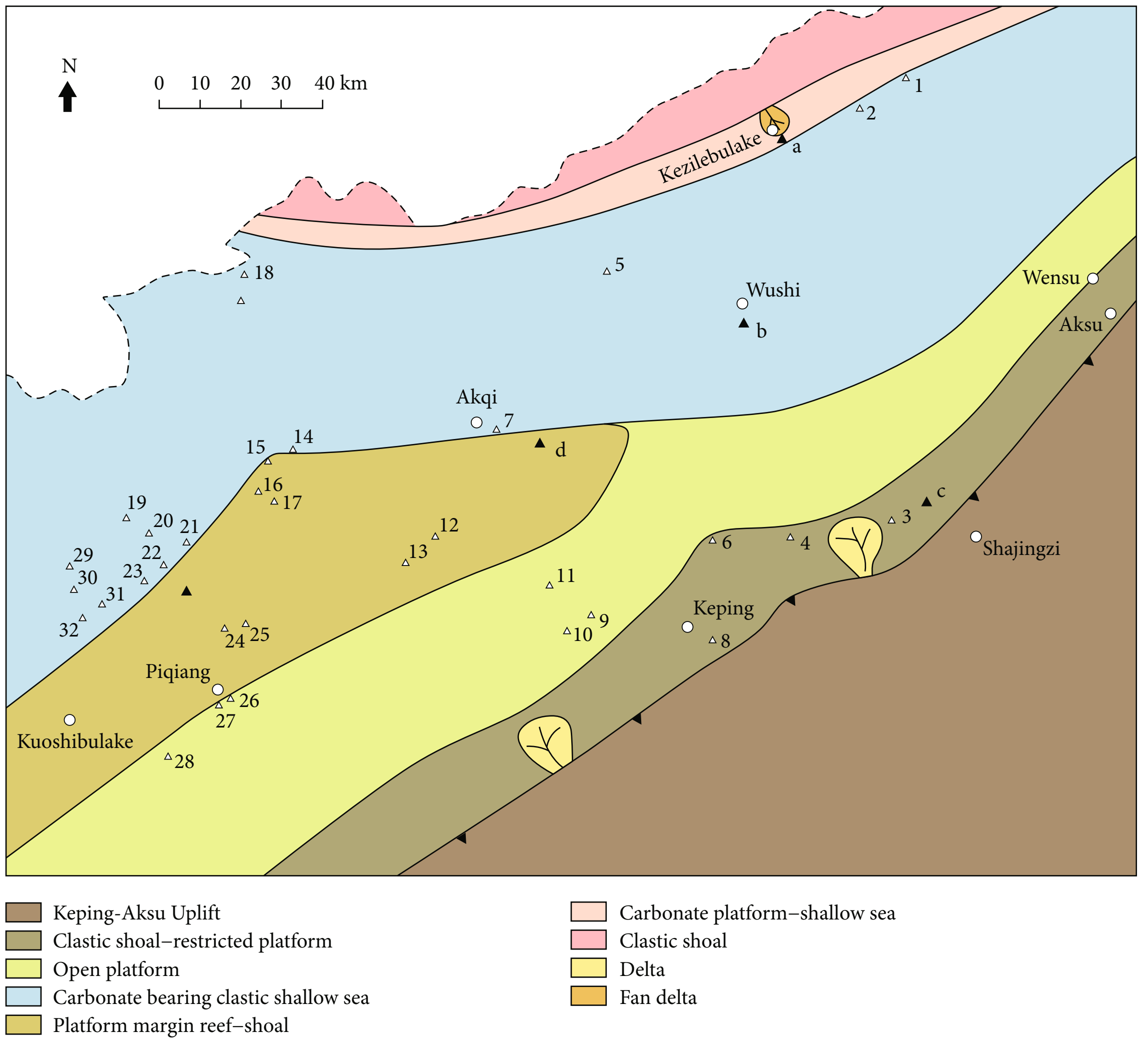



Figure 6: Sedimentary facies distribution of Zhaerjiake period in Wushi region (section names are shown in Figure 2).

describe the color, brightness, and distribution characteristics of hydrocarbon fluorescence.

## 4. Results

### *4.1. Lithologic Characteristics*

*4.1.1. Platform Margin Reef.* The platform margin reef in Wushi area was mainly composed of boundstone and skeleton boundstone, followed by bafflestone. The boundstone was mainly grayish black, grayish white and grayish red thick to massive algal bound reef limestone (Figures 3(a) and 3(b)). The reef-building organisms are dominated by algae. The algae fossils had native characteristics, accounting for more than 70% of the reef-building organisms, and a few sponges and grid bryozoan skeletons were occasionally seen. The reef attached organisms included crinoids, cephalopods, and brachiopods in algal bound reef limestone. The skeleton boundstone were mainly sponge-algal bound reef limestone. The sponge skeleton was filled with bioclastic and grayish red micrite, and sparite-bounding layers was curved and around the skeleton (Figure 3(c)). Through microscopic observation, it was found that the algae bonding layer developed along the edge of carbonate grain (Figure 3(d)). Some dense algal bound reef limestones had strong diagenesis, and two-stage cementation characteristics could be seen (Figure 3(e)). The bafflestone was mainly brown crinoid micrite limestone, with crinoid stem content of 40%~70%, and the maximum diameter of crinoid stem was about 5 mm. Some crinoids were elongated, reflecting the weak hydrodynamic conditions behind the reef (Figure 3(f)).

*4.1.2. Platform Margin Shoal.* The platform margin shoal in Wushi area was mainly composed of bioclastic shoal and gravel shoal, followed by sand gravel shoal. The lithology of bioclastic shoal was gray, gray-black, gray-red bioclastic limestone, or bioclastic micritic limestone. Bioclastic types included crinoids, abrasives brachiopods, bivalves, algae, foraminifera, skink, and crinoids. The bioclastic content of some bioclastic limestones could reach more than 60%, reflecting shallow water high-energy environment (Figures 3(g)–3(j)). Gravel shoals had the characteristics of algae binding, which might be the transition type from shoal to platform margin reef. The lithology of gravel shoal was

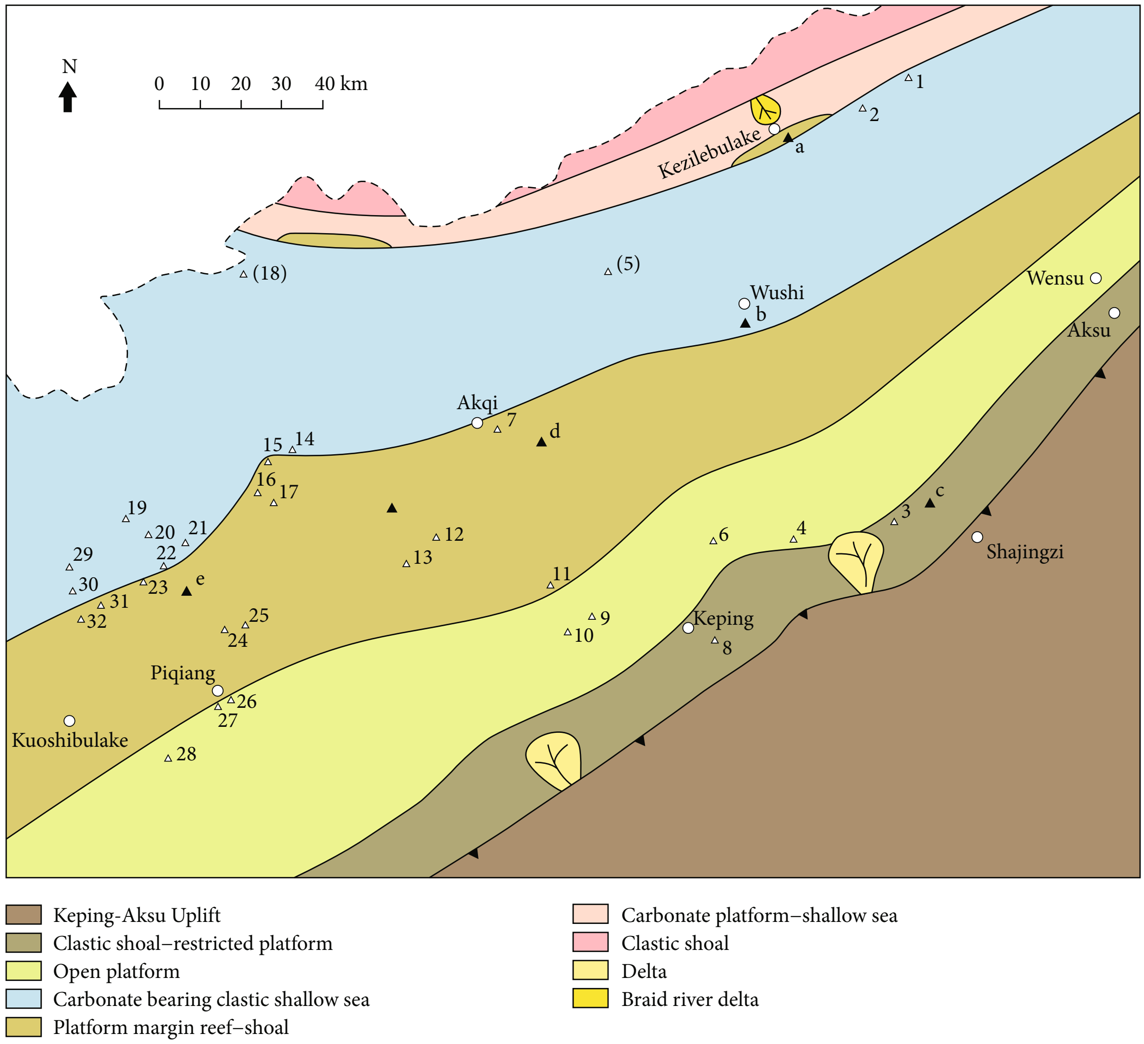



Figure 7: Sedimentary facies distribution of Balediertage period in in Wushi region (section names are shown in Figure 2).

light gray and grayish red algae bonded calcirudite. The gravels were well sorted, subangular, and subround, and the gravel diameter was 2-5 cm. Bright crystal cementation among gravels and local residual pores was filled with brown micritic, and secondary pores were easily formed by weathering and leaching along the algal cavity (Figure 3(k)). The lithology of sand gravel shoal was gray-brown bioclastic-gravel-bearing arenaceous limestone with crossbedding lamina, and beaded dissolution holes developed along structural fractures or bedding (Figure 3(l)).

### 4.2. Sedimentary Sequence

*4.2.1. Zhaerjiake Period.* There are 4 reef-forming cycles of Zhaerjiake Formation in Aoyibulake section (Figure 4(a)). In each cycle, the single-layer reef limestone thickened upward and was a prograding reef. In cycle I, the thickness of reef was 32 m. The thickness of reef base was 28 m, which was sparry bioclastic limestone. The sedimentary sequence of bioclastic-bearing sparry limestone-bioclastic sparry limestone-algal bonded reef limestone could be seen vertically. In cycle II, the thickness of reef limestone was 63 m. The reef base was 56 m thick. The sedimentary sequence of slump breccia limestone-crinoid micritic limestone-algal bonded reef limestone can be seen vertically. The thickness of reef limestone in cycle III is 40 m. The thickness of reef base was 35 m. The sedimentary sequence of grainstone, sparry bioclastic limestone, and algal bonded reef limestone was developed vertically. In cycle IV, the thickness of reef limestone was 25 m. The reef base was 39 m. The reef cover was collapsed rock rich in deformed micritic lamina, 26 m thick, which vertically consisted of bioclastic limestone-algal bonded gravel limestone-algal bonded reef limestone-breccia-bearing micritic limestone-granular micritic limestone sedimentary sequence. At the top of the platform margin shoal and upper open platform formed a sedimentary sequence consisted of bioclastic limestone-bioclastic micrite-bioclastic micrite limestone-micrite, reflected the deepening of water body during Zhaerjiake period.

There are 3 reef-forming cycles of Zhaerjiake Formation in Sepabayi section (Figure 4(b)). In each cycle, the single-layer reef limestone had the characteristics of upward thickening and the number of layers increased, and it was a progradation reef. In cycle I, the thickness of reef limestone was

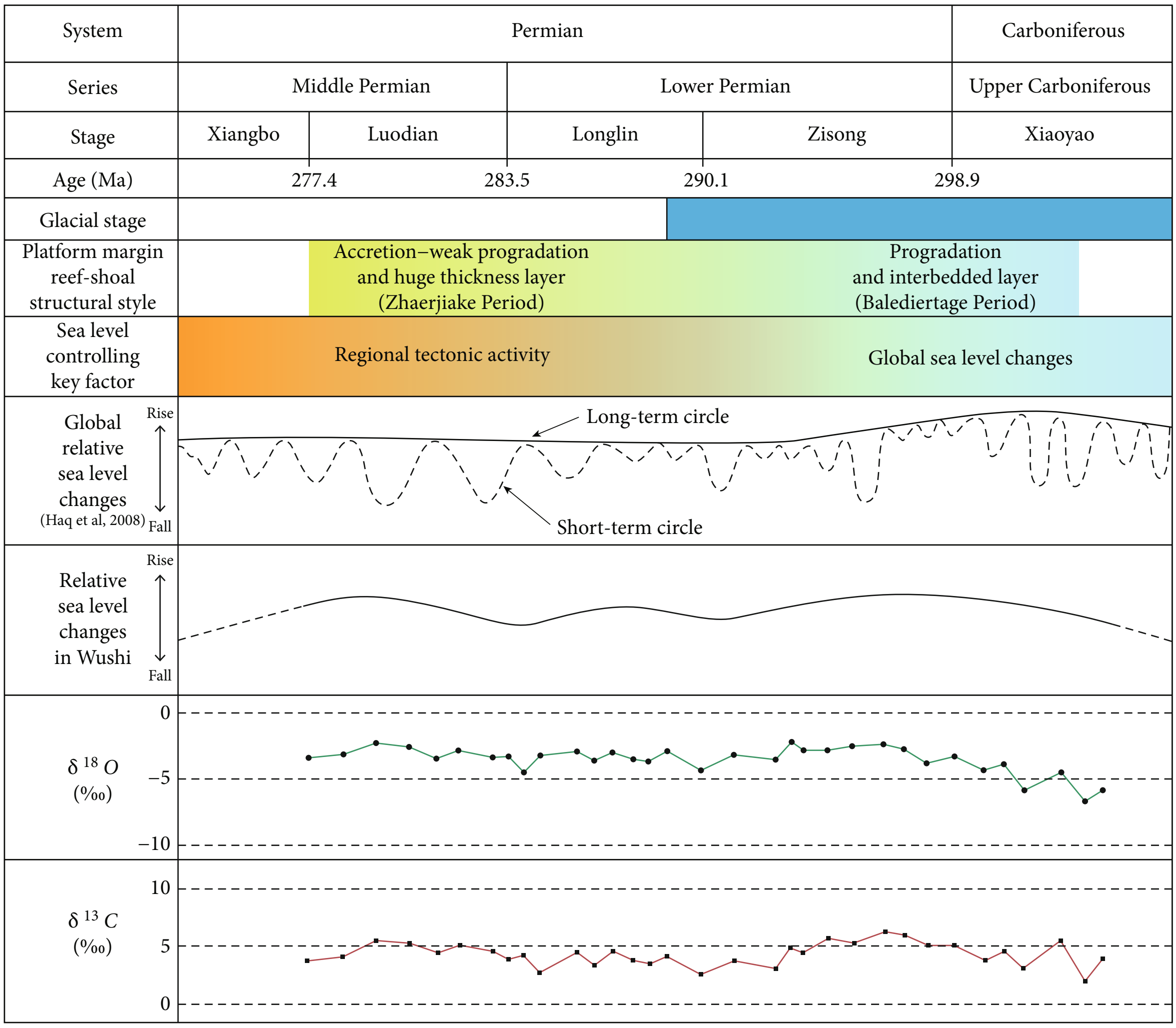



Figure 8: Developmental controlling factors of Carboniferous-Permian reef and shoal in Wushi area.

38 m, and the thickness of reef base was 35 m. The thickness of reef limestone in cycle II was 47 m, and the thickness of reef base was 38 m. The sedimentary sequences of bioclastic micritic limestone-bioclastic limestone-algal bonded reef limestone developed vertically in cycle I and II. The thickness of reef limestone in cycle III was 51 m, and the thickness of reef base was 43 m. The sedimentary sequence of grainstone-algal bonded gravel limestone-algal bonded reef limestone was developed vertically. The shoal facies reef cap on the top and the intershoal sea consisted of bioclastic sand gravel limestone-bioclastic micritic limestone–bioclastic-bearing micritic limestone-micritic limestone. It reflected the deepening of water body at the end of reef formation period.

*4.2.2. Balediertage Period.* The Kunkelaqi Formation developed a huge thickness reef-forming cycle in the Aoyibulake section (Figure 5(a)). The accumulative thickness of massive algal reef limestone is 418 m, and the thickness of single-layer reef limestone is nearly equal or slightly increased upward. The thickness of dense single-layer reef limestone at the top could reach more than 20 m, with accretion and weak progradation characteristics. The lithology of underlying platform margin shoal was bioclastic micritic limestone and formed the reef base with a thickness of 77 m. The lithology of overlying restricted platform was argillaceous limestone and marl intercalated with argillaceous siltstone or fine sandstone, which formed the reef cover. The clastic rock intercalated with marl became coarser and thicker upward, reflecting that the water body became shallower in the late stage of reef formation.

The huge thick reef-forming cycle was developed in the Kunkelaqi Formation of Sepabayi section (Figure 5(b)). The accumulative thickness of massive reef limestone was 418 m. The thickness of single reef limestone was nearly equal or slightly increased upward. The maximum thickness of reef limestone at the top was more than 15 m, which was aggradation-weak progradation type reef. The underlying bioclastic micritic limestone of platform margin shoal formed the reef base, with a thickness of 65 m. The overlying tidal flat facies marl, mudstone, and fine sandstone constituted the reef cover. The content of sandstone in the reef cover increased upward and the number of layers increased, reflecting that the water body became shallower in the late stage of reef formation.

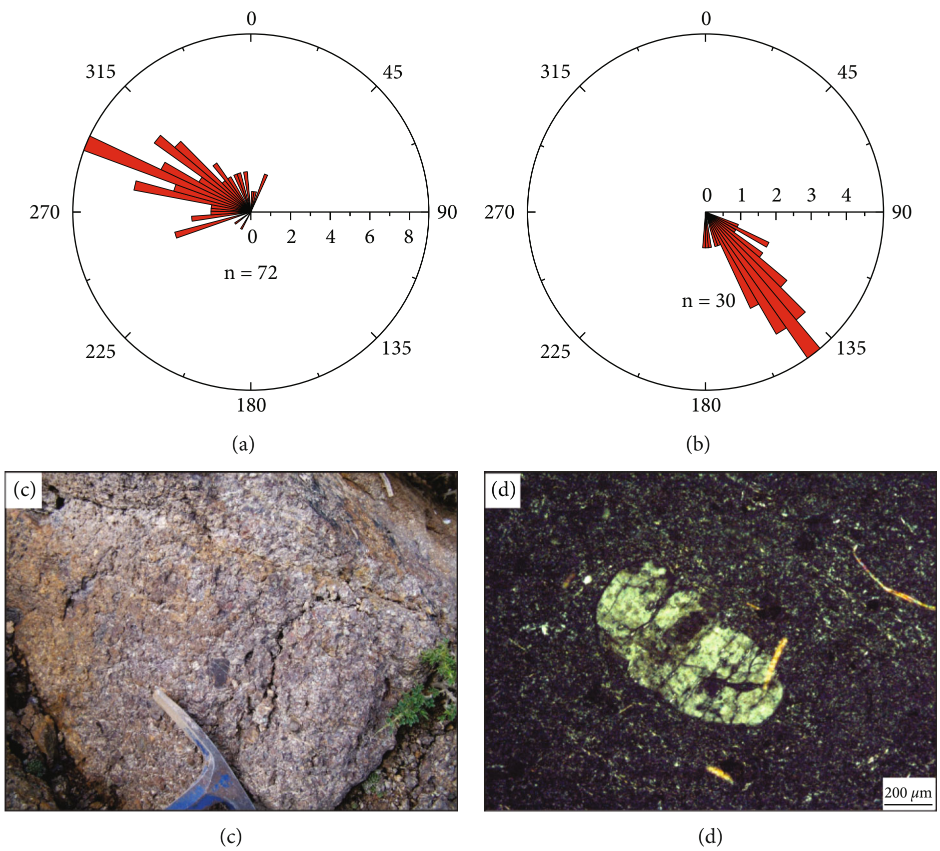



Figure 9: Sandstone laminae occurrence rose diagrams and proximal clastic photos. (a) Sandstone laminate attitude rose diagram, Kangkelin Formation, Sishichang section. (b) Sandstone laminate attitude rose diagram, Balediertage Formation, Kezibulake section. (c) Volcanic breccia, Balediertage Formation, Kezibulake section. (d) Tuff, cross-polarized light, Balediertage Formation, Kezibulake section.

There are 2 reef-forming cycles in the Balediertage Formation of Kezilebulake section (Figure 5(c)). In cycle I, the thickness of platform margin reef was 53 m. The monolayer reef was accretion reef, and the thickness of reef base was 22 m. Vertically, it formed the sedimentary sequence of crinoid micrite limestone-sponge algae bonded reef limestone. In cycle II, the thickness of reef body was 170 m, which increased upward slightly, with aggradation-weak progradation characteristics. The base thickness of shoal facies reef was 62 m. The sedimentary sequence of algal bound gravelly limestone-bioclastic gravelly sandy limestone-spongy algal bound reef limestone developed vertically. The top colluvial facies reef cap was a medium thick grain micritic limestone containing reef breccia.

In conclusion, interbedded platform margin reefs and shoals were mainly developed in Wushi area during Zhaerjiake period, and the platform margin reef was mainly progradation type. The reef-forming cycles suggested frequent relative sea-level fluctuations. In the Balediertage period, the development of extremely thick platform margin reef was dominant, and the accumulated thickness of reef limestone showed a decreasing trend (418 m-398 m-170 m) from west to east (Figure 5). Platform margin reef was accretion and progradation type, which was obviously different from the interbedded reef-shoal of Zhaerjiake Formation. The few reef-forming cycle might be related to the long-term stable rise of relative sea level.

### *4.3. Plane Distribution Characteristics*

*4.3.1. Zhaerjiake Period.* The palaeogeographic pattern in Wushi area during the Zharjiak period showed that the residual marine basin was sandwiched between the Keping-Aksu Uplift and the southern Tianshan orogenic belt. The northwest margin of Tarim had the characteristics of basement landform of “low in the West and high in the East”. With the rise of regional sea level in the Late Carboniferous, the seawater invaded from west to east, making the uplift area of the Early Carboniferous submerged. With the continuous expansion of carbonate sedimentary range, wide and gentle carbonate platforms are developed in the northern margin of Keping-Aksu Uplift, while narrow and long carbonate platforms are developed in the top of the south Tianshan orogenic wedge. From northeast to southwest, the study area successively developed clastic rock shore facies, carbonate platform carbonate-shallow marine facies, clastic rock shallow marine facies, platform margin reef-shoal facies, open platform facies, and clastic rock shore-limited platform facies (Figure 6).

According to the shore facies, tidal flat facies and restricted platform facies developed in Kangkelin Formation of Sishichang section; the seawater had invaded near Shajingzi-Keping line at this time. In the Piqiang area in the southwest, the platform margin reef-shoal facies began

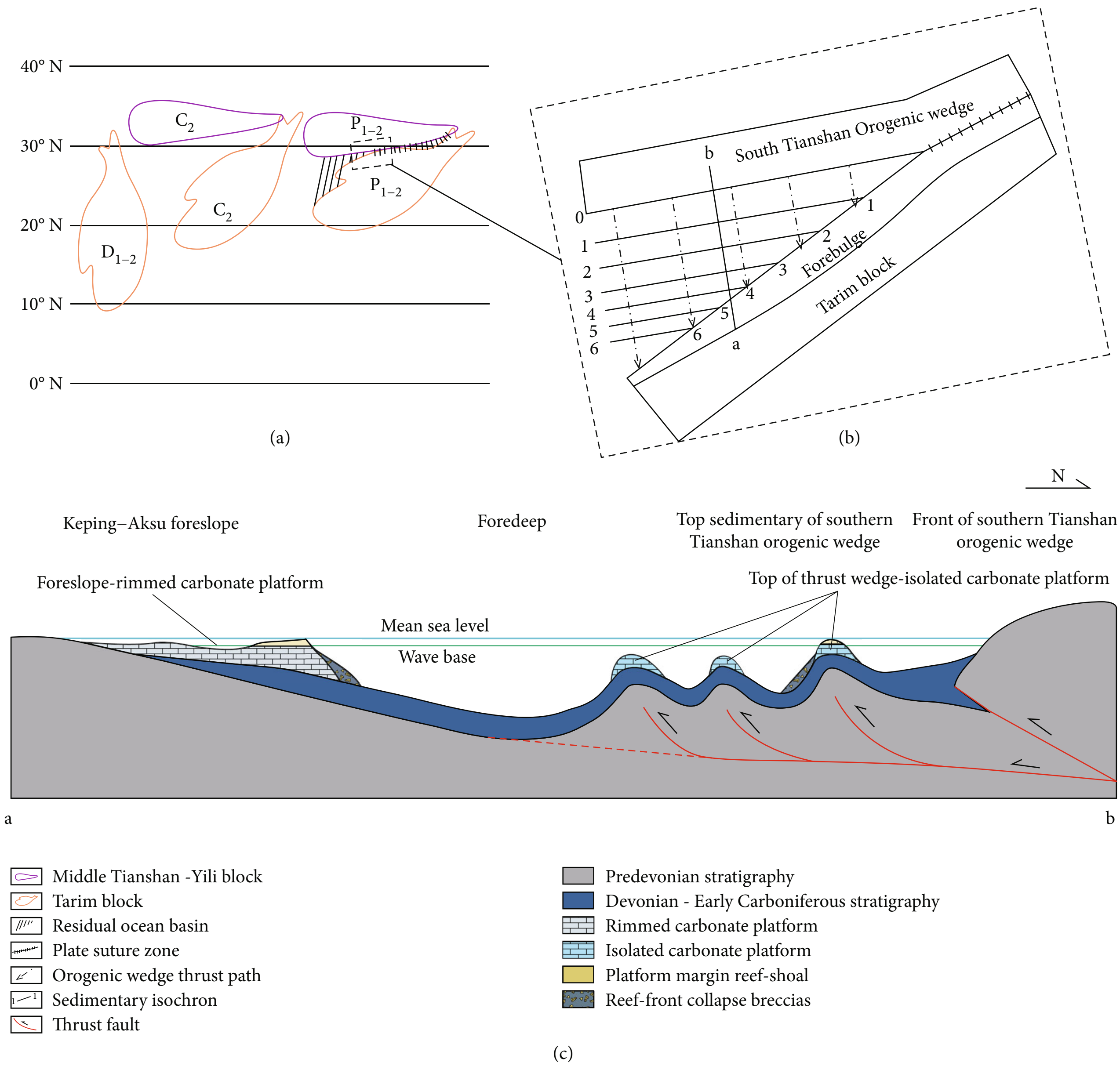



Figure 10: Late Paleozoic plate tectonic setting, closure model of residual sea basin and paleogeomorphology section diagram in northwestern of Tarim Basin.

to develop along the front slope of Keping-Aksu Uplift. The reef-shoal body was distributed in a strip in the northeast direction, and the width of the facies belt in the northeast direction reduced. According to the lithofacies of the control sections, the platform margin reef-shoal could extend to the northeast at least near Aheqi. The extension length of the whole facies belt was at least about 200 km, and the overlapping width was about 30-50 km (Figure 6).

*4.3.2. Balediertage Period.* The palaeogeomorphology in Wushi area during Balediertage period basically inherited Zhaerjiake period. The range of clastic rocks in the foredeep was obviously smaller than that in the early stage. The open platform, limited platform, and clastic rock shore facies in the northern margin of Keping-Aksu Uplift retreated slightly (Figure 7). However, the sedimentary range of the platform margin was slightly expanded, which might be related to the high carbonate deposition rate in the platform margin. The control sections are located at the easternmost edge of the platform margin reef-shoal facies, the distance between Tikeliketage-Qiudayisayi section (section (11)) and Sepabayi (section d) was 38 km. In the former section, the thickness of the platform margin reef of Kunkelaqi Formation was 200-300 m [11], while the measured thickness of the latter section, the Kunkelaqi Formation reached 398 m (Figure 5(b)), indicating that the platform margin reef-shoal facies still had at least 38 km overlapping width in the east of Aheqi.

According to the distribution of sedimentary facies, it was inferred that the platform margin reef-shoal of

Table 1: Physical analysis data of platform margin reef-shoal reservoirs in Wushi area.

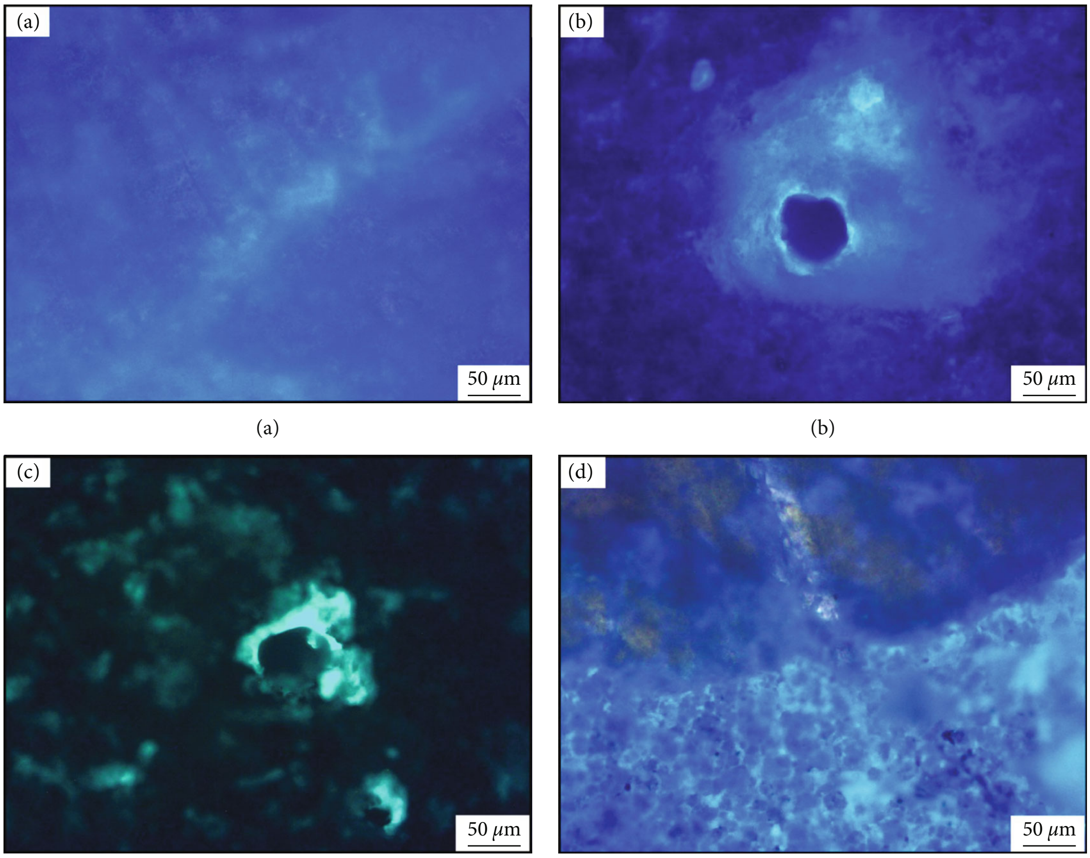
| Section | Formation | Sample | Porosity (%) | Permeability (mD) | Sedimentary facies | Lithology | Evaluation results |
|---|---|---|---|---|---|---|---|
| e | Kunkelaqi | C1004 | 4.21 | 3.740 | Platform margin reef | Reef limestone | II |
| e | Kunkelaqi | C1006 | 3.63 | 1.310 | Platform margin reef | Reef limestone | II |
| e | Kunkelaqi | C1009 | 1.14 | 0.082 | Platform margin reef | Reef limestone | III |
| e | Kunkelaqi | C1010 | 0.56 | 0.036 | Platform margin shoal | Bioclastic limestone | III |
| e | Zhaerjiake | C1012 | 3.42 | 2.550 | Platform margin shoal | Bioclastic limestone | II |
| e | Zhaerjiake | C1015 | 0.89 | 0.033 | Platform margin reef | Reef limestone | III |
| e | Zhaerjiake | C1016 | 0.51 | 0.028 | Platform margin shoal | Grain limestone | III |
| e | Zhaerjiake | C1019 | 0.97 | 0.077 | Platform margin reef | Reef limestone | III |
| d | Kunkelaqi | C1119 | 1.56 | 0.074 | Platform margin reef | Reef limestone | III |
| d | Kunkelaqi | C1115 | 0.77 | 0.039 | Platform margin reef | Reef limestone | III |
| d | Kunkelaqi | C1113 | 0.64 | 0.038 | Platform margin shoal | Bioclastic limestone | III |
| d | Zhaerjiake | C1111 | 0.83 | 0.072 | Platform margin shoal | Bioclastic limestone | III |
| d | Zhaerjiake | C1109 | 1.28 | 0.063 | Platform margin reef | Reef limestone | III |
| d | Zhaerjiake | C1101 | 1.84 | 0.051 | Platform margin shoal | Grain limestone | III |
| a | Balediertage | C1308 | 3.32 | 1.680 | Platform margin reef | Reef limestone | II |
| a | Balediertage | C1312 | 2.81 | 1.950 | Platform margin reef | Grain limestone | II |
| a | Balediertage | C1313 | 0.72 | 0.023 | Platform margin reef | Reef limestone | III |
| a | Balediertage | C1323 | 0.92 | 0.027 | Platform margin reef | Reef limestone | III |
| a | Balediertage | C1326 | 1.36 | 0.081 | Platform margin shoal | Bioclastic limestone | III |

Bladiertage stage might penetrate the whole area, and the distribution area was the largest (Figure 7). In the northern part of Wushi area, small platform margin reef-shoal with discrete distribution began to develop at the top of the south Tianshan mountains thrust wedge. Under the influence of paleogeomorphology and near provenance, the platform margin reef-shoal could be transformed into braided river delta front laterally (Figure 7).

## 5. Discussion

### *5.1. Controlling Factors on Development of Platform Margin Reef-Shoal*

*5.1.1. Relative Sea-Level Change.* Reef-shoal is sensitive to paleowater depth changes, and its development characteristics and superimposed patterns are a direct response to changes in relative sea level [21]. Relative sea-level rise and fall is a joint response of global sea-level fluctuation and regional tectonic activity, which is especially important for foreland deposits [22]. In order to determine the influence of relative sea-level fluctuation on the evolution of platform margin reef and shoal, C and O isotope tests were carried out on 33 samples collected from the Aoyibulake section. The sea-level change curves were plotted in combination with sedimentary facies changes. By comparing the relationship between relative sea-level changes in Wushi region and global sea-level changes [20], it can be seen that the trend of sea-level change in Wushi area was basically consistent with that of global sea-level change in Zhaerjiake period (Xiaoyao period-Zisong period), which was in a continuous rising state. Sedimentary and provenance records of the Lower Permian in the Sishichang section indicate that there was no large-scale uplift of the southern Tianshan mountains before at least the Early Permian Zinsong (Asselian) period [23, 24]. Therefore, the relative sea level during the Zhaerjiake period was mainly controlled by global sea-level changes (Figure 8). During this period, tectonic activity was weak, the basin basement subsidence driven by sedimentary load was slow, and the relative sea level rose slowly. At this time, the sedimentation rate of platform margin reef was slightly higher than that of the relative sea-level rise. Therefore, progradational platform margin reef developed along the slope of the front of Keping-Aksu Uplift. On the other hand, the secondary glaciation-interglacial cycle caused frequent sea-level fluctuations due to the Gondwana III glacial event (about 307~289 Ma) [25]. The frequent fluctuation of sea level led to the alternating reef-forming cycle and shoal-forming cycle, so the platform margin reef and shoal showed an interbedded structure (Figure 4). Balediertager period (Longlin-Luodian stage), Wushi area, existed significant difference with the global relative sea-level change; tectonic activity might gradually became the main control factors of relative sea level (Figure 8) and continental rise tectonic flexure basin basement subsidence, along with the steady rose in relative sea level, while the relative sea-level rise rate close to or slightly below the platform margin reef sedimentary rate. Therefore, accretion-weak prograding reef mainly developed. In addition, the basement subsidence caused a stable rise in relative sea level, and the single reef-forming cycle was long, resulting in the development of extremely thick platform margin reefs (Figure 5). During the Kalendar stage, regional regression led to the rapid decline of relative sea level, and the shallow water led to the rapid extinction of platform margin reefs and shoals.




(a) (b) (c) (d)

Figure 11: Fluorescence phenomenon of the platform margin reef-shoal reservoir under the fluorescence microscope. (a) Fluorescence of calcite cement veins, C1001, Kunkelaqi Formation, section e. (b) Fluorescence of calcite cement dissolution pore, C-1001, Kunkelaqi Formation, section e. (c) Fluorescence of calcite cement dissolution pore, C1006, Kunkelaqi Formation, section e. (d) Fluorescence of two-phrase carbonate fillings, C1322, Balediertage Formation, section a.

*5.1.2. Palaeosource.* The accumulation of siliceous clasts from orogenic wedges or cratons leads to mixing of carbonate and siliceous clastic deposits or to the termination of carbonate deposits [26]. Some researchers believe that terrigenous clastic deposition far away from the mainland is the most fundamental controlling factor for the formation of carbonate platform [27]. Therefore, studies have shown that in a high-nutrient environment with a small amount of remote siliceous debris injection, corals adapted to a high cleanliness and low-nutrient environment are gradually replaced by algae and sponges that prefer a high-nutrient environment [28]. In other words, the input of a small amount of siliceous debris is beneficial to the development of algal reefs. Therefore, there are two sides to the influence of the source of antiquities on the development of platform margin reef and shoal. No terrigenous coarse debris was found in the Zarjak, Kakak, and Kunklaqi formations in the Aoyibulake and Serpapayi sections (Figures 3 and 4). The rose diagram of the Conklin Formation sandstone laminate occurrence in Sishichang section shows that the main direction of the palaeocurrent is NW (Figure 9(a)), indicating that the provenance came from the Tarim Craton in the south. Guo [24] further demonstrated that the clastic rock components and heavy mineral assemblages in the Kangklin Formation reflect stable tectonic setting, and the detrital zircon dating of sandstone revealed that the provenance was mainly from the paleouplift within the Tarim block [24, 29]. Therefore, the platform margin reef-shoal located in the slope of the front edge of Keping-Aksu Uplift belongs to the remote source type, and a small amount of siliceous fine debris input could promote the large-scale development of algal reef. In contrast, the rose pattern of sandstone laminate occurrence in the Baledilta Formation showed a SSE direction of paleocurrenic flow, indicating that the provenance came from the southern Tianshan polycyclic orogenic belt in the north (Figure 9(b)). The sandstone detrital model of the Kalazhierjia Formation in the western section of Maidantawu subregion also indicates that the provenance is mainly from the multicycle orogenic belt [30]. Near source coarse clastic deposition of fan delta and braided river delta developed under carbonate platform of Kalazhierjia Formation and Balediertage Formation in Kezibulake section (Figure 4 and Figure 5), among which volcanic breccia and tuff all reflect the characteristics of near source (Figures 9(c) and 9(d)). Therefore, the coarse clastic from the southern Tianshan orogenic belt was easy to be imported into the platform margin of the slope in front of the orogenic wedge. The mixed sedimentation restricted the growth and expansion of platform margin reef-shoal to a certain extent.

*5.1.3. Paleogeomorphy.* The relatively high palaeogeomorphology in the basin is prone to reef-shoal facies, and the high productivity of carbonate in the reef-shoal region promotes the palaeogeomorphology difference [31, 32]. During Devonian to Carboniferous, the Middle Tianshan-Yili block and Tarim block collided continuously (Figure 10(a)). On the one hand, the northern margin of Tarim block developed giant foreuplift inherently on the basis of Keping-Aksu Uplift due to tectonic flexural action (Figure 10(b)). On the other hand, extrusion resulted in the development of a series of fault-spreading folds parallel to the orogenic belt in the southern Tianshan thrust wedge top zone (Figure 10(c)), which constituted the relatively high part of the Paleozoic paleogeomorphology in the area. Controlled by scissor-type closure, there was still a west-opening residual marine basin in the northwestern margin of Tarim Basin from Late Carboniferous to Middle Permian [14]. During the Zhaerjiake period, the platform margin reef-shoal began to develop along the high slope of the front slope of Keping-Aksu Uplift. Due to the low basement topography and smooth seawater circulation in the southwest (Piqiang area), the platform margin reef-shoal was characterized by large-scale and continuous distribution (Figure 6 and Figure 10(c)). The topographic elevation of the uplifted basement became steeper, the sea basin became narrower, the seawater circulation became worse, and the facies zone became narrower. At the same time, in the front of the southern Tianshan orogenic belt, isolated platforms began to develop on the wedge top underwater anticline with suitable water depth (Figure 10(c)). During the Balerdiertage period, because of the deflection of the southern Tianshan orogenic wedge, the paleogeomorphic conditions suitable for the development of platform margin reef-shoal might have appeared in the northeast slope of the Keping-Aksu Uplift. And the platform margin reef-shoal extended further to the northeast. On the side of the orogenic wedge of the southern Tianshan mountains, because of the scale limitation of the anticline, the platform margin reef-shoal developed in the isolated platform was difficult to form belts. The isolated platform margin reef-shoal is characterized by small-scale and discrete distribution (Figure 7 and Figure 10(c)).

*5.2. Exploration Potential of Platform Margin Reef-Shoal.* According to the classification standard of Paleozoic carbonate reservoir rocks in Keping area [33], the quality evaluation of the Upper Carboniferous to Middle Permian platform margin reef-shoal reservoirs in Wushi area was medium (II) to poor (III) (Table 1). The porosity of platform margin reef-shoal reservoir was 0.72%~4.2%, and the permeability was $0.023 \sim 3.74 \times 10^{-3}$ mD. The porosity of platform edge shoal reservoir was 0.56%~3.4%, and the permeability was $0.028 \sim 2.55 \times 10^{-3}$ mD. There was no significant correlation between reservoir physical property and sedimentary facies type and lithology. Thin sections showed that the primary pores of the reservoir were mostly cemented in the later stage (Figure 3(e)), and the deviation of reservoir physical property might be related to the strong diagenesis in later stage.

Previous studies had shown that the reef limestone and micritic limestone of the Lower Permian-Middle Permian were intermediate-good source rocks themselves, but the outcrops were mainly low-mature source rocks (*R*o is 0.42%~1.15%), which may be due to the lack of overlying Cenozoic cap rocks [33]. The huge thick tidal flat mudstone in Kalundaer Formation was stable and could be used as a regional cap rock. The oil-source correlation showed that the oil seedlings of Balikelike Formation exposed near Piqiang were from the source rocks of this formation [34]. The C isotope correlation reveals that oil and gas migrated at a short distance, and the oil seedlings should be self-generated and self-stored [33].

By fluorescence thin sections observation, the blue and blue-green fluorescence was significant along the calcite cement vein and near the dissolution hole of the reservoir. This phenomenon showed that after the formation of cement, oil and gas migration and accumulation did occur along fractures or dissolution holes and caves (Figure 11). In fact, several samples with medium physical properties came from the Aoyibulake and Kezilebulake sections adjacent to the fault zone (Figure 1). This might be due to the development of rock fractures near the fault zone, and the deep hydrothermal solution was also easy to migrate and dissolve. Although the physical properties of platform margin reef-shoal reservoirs were poor, their huge distribution scale made up for this defect to a certain extent. To sum up, in the covered area, the platform margin reef-shoal reservoirs adjacent to the fault zone and with large sedimentary thickness might have good hydrocarbon exploration prospects.

## 6. Conclusions

(1) The platform margin reefs in the Wushi area were dominated by algae reefs, and the platform margin shoals are dominated by bioclastic shoals and gravel shoals. The characteristics of algal bind between grains were common

(2) During the Zhaerjiake period, interbedded reefs and shoals were the main type, and platform marginal reefs were of the progressive type. During the Balediertage period, huge thick platform margin reefs were the main type, and platform margin reefs were of accretion-weak progressive type

(3) The development controlling factors of the platform margin reef-shoal are mainly relative sea-level change, palaeosource, and paleogeomorphy. Relative sea-level changes controlled the development characteristics and superposition mode of the platform margin reef-shoal; there were two sides of the influence of the palaeosource on the platform margin reef-shoal; the paleogeomorphology controlled the development position and spreading scale of platform margin reef-shoal

(4) In the covering area, the platform margin reef-shoal reservoirs adjacent to the fault zone and with large sedimentary thickness might have a good prospect for hydrocarbon exploration

## Data Availability

Data are available on request.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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