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Article

Depositional Architecture of the Middle and Late Ordovician Reef–shoal Complexes and the Distribution Characteristics of the Reservoirs in the Tazhong Area, Tarim Basin

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Abstract: Reef-shoal complexes were extensively developed during the Middle and Late Ordovician in the Tarim Basin. Based on core observations from 18 drilling wells, petrographic analysis of more than 500 large thin sections, and correlation of outcrop sections, this study investigates the reefal deposits of the Middle–Upper Ordovician. The results indicate that the formation of these reefs is primarily associated with reef-building organisms, including receptaculites-sponges, corals, stromatoporoids, and calcimicrobes. Reef-shoal complexes consist mainly of framework reefs, lime-mud mounds and grainstone shoal or banks, with "small" reef and "big" shoal, as well as shallowing upward sequences. Laterally, these complexes are discontinuously distributed in sheets along the carbonate platform margin of the No. I fault zone in the northern margin of the Tazhong area; vertically, they exhibit multi-storey superimposed stacking, demonstrating a distinctive depositional architecture and forming the most important reservoir facies belt in the region. Furthermore, this study reveals that meter-scale sea-level cycles resulting in episodic meteoric freshwater dissolution, epikarstification during the late depositional stage of the Lianglitage Formation in the Tazhong area, as well as faulting and fracturing, collectively played a critical role in controlling the formation of favorable porous-vuggy and fractured layered reservoirs within the reef-shoal bodies. These insights have provided crucial guidance for the discovery of the largest Ordovician reef-shoal condensate gas field in China within the Tarim Basin.

Keywords: reef-building organisms; reef-shoal complexes; reservoir belt; condensate gas field; Tarim Basin

1. Introduction

Reefs and grainstone shoal deposits are important targets for global oil and gas exploration. At present, nearly half of the world's proven oil and gas (about 5 billion tons) are reserved in reef-shoal facies. The sedimentary rate of the reef and shoal facies at the rimmed platform margins, and or within the platform is

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relatively fast [1–4], which may facilitated the formation of a large number of primary porosities due to the syngenetic karstification, plus the subsequent superimposed modification of near-surface karstification, dolomitization and burial dissolution, so the reef-shoal deposits tend to become the favorable reservoir facies [5–9]. For example, Mexican Giant Petroleum Field and the fields in American Permian Basin, and Devonian System in the west of Canada are all reef reservoirs, and more than half of the reservoirs exist in the reefs or grainstone shoal facies deposited along the platform margin controlled by the slope-break zone [10].

China's reef-related oil and gas fields are mainly located in Puguang Gas Field in the east of Sichuan Province, Liuhua 11-1 Oilfield in north of the South China Sea, the southern coast of Jiyang Depression in Shandong Province and Pearl River Mouth Basin [11–15]. The depositional sequences generating the oil and gas in the fields are mostly in the Late Paleozoic to Cenozoic reef facies. In the past about twenty years, the oil community has found important oil and gas fields successively in the older Ordovician carbonate reef and shoal sedimentary facies in the Tarim Basin, such as the large Ordovician carbonate reservoirs in the Tazhong uplift zone [16–20]. However, there is a lack of understanding about the structure, forming mechanism and constraints of these reef and shoal facies along the margin of the carbonate platform. In fact, as for whether large-scale reefs formed in the Early Paleozoic Era, there is still no clear conclusion in the academic community yet.

Based on plenty of geological and geophysical data accumulated from years of exploration and development of oil fields, including the cores of more than 30 wells and over 500 large slices, the 3D seismic data in Tazhong as well as the field sections along the western basin margin, this study discusses the architecture, distribution and reef organisms of the reef-shoal complexes found in the Lianglitage Formation (Ordovician) developed along the northern Tazhong slope-break zone in the Tarim Basin, and attempt to reveal the factors that control the formation and distribution of the reef-shoal complexes. The model for the development of the reef-shoal complexes in this article have been applied to guide the oil and gas exploration, providing an important guidance for the discovery of the large-scale reef-shoal condensate gas fields in the study area.

2. Geological Background

The Tarim Basin is a large sedimentary basin located in the west of China, covering an area of 560,000 square kilometers. The basin experienced a long-term geological evolution and multi-period deformation from Sinian to Neogene [21–24]. The Paleozoic tectonic framework of the basin is mainly featured as the formation of many large NWW-trending and NEE-trending paleo-uplifts and depression zones [25]. The main paleo-uplifts include the Tazhong uplift, Bachu uplift, Tabei uplift and Taxinan uplift (Figure 1). The Tazhong uplift, forming in the Early Paleozoic Era, is located in the east section of the central uplift belt of the basin. The paleo-uplift is generally NWW trending, with a wide and gentle-sloped west part, and a steep and narrow east part; a length of over 300 km in the east and a width of 80~100 km in the west. On the northern and southern sides, the uplift is bounded respectively by Fault Zones No.1 and No.2. The Middle and Late Ordovician basin was featured as a broad carbonate platform environment, and along the platform margin, reef-shoal facies widely formed [25–27]. Paleomagnetic data indicate that the Ordovician Tarim block was roughly located in the ancient southern latitude 20°~30°, and its environment mainly belonged to tropical and subtropical climates, meeting the paleoclimate conditions for the formation of reefs like corals [28–31].

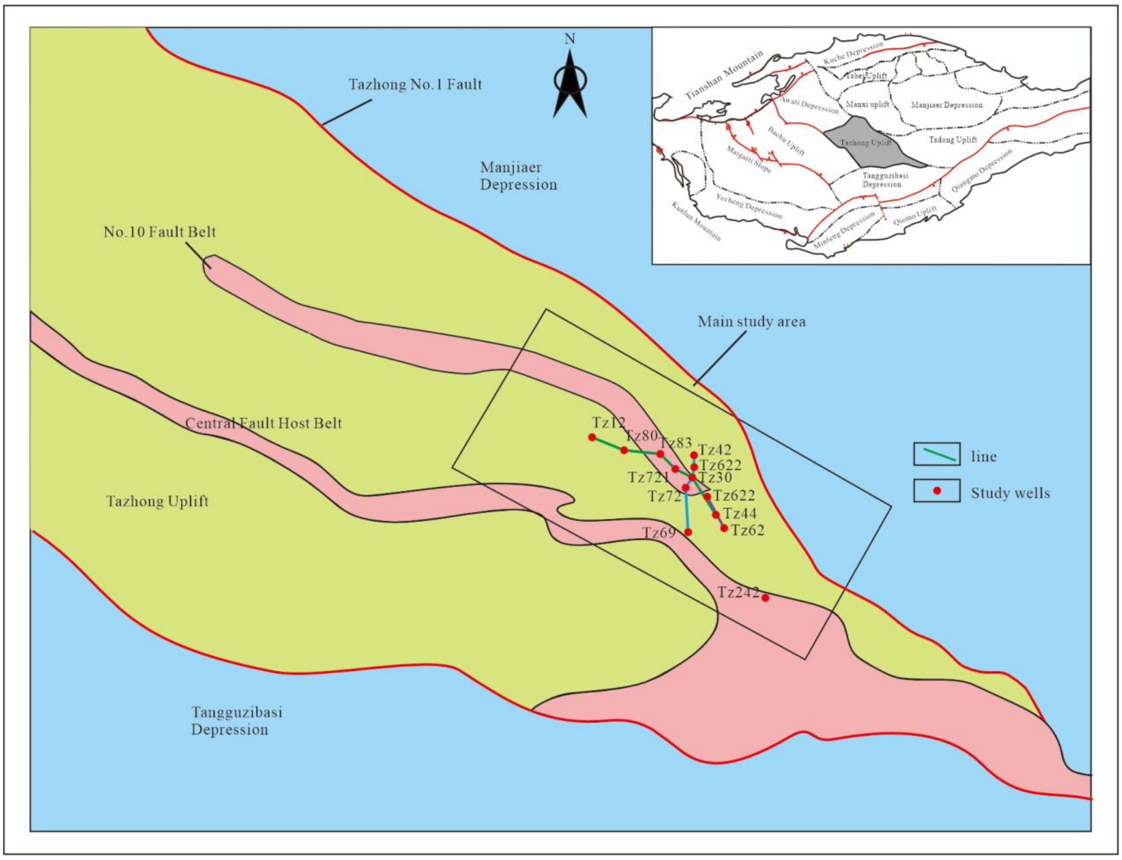

Figure 1. Division and distribution of tectonic units in the Tarim Basin [16].

3. Study Methods

The study based on the observation on nearly 1000 m sectioned cores of more than 18 wells in the middle part of Tazhong area, and the identification on more than 500 slices of samples and the analysis on the samples in terms of rock components, types of biological fossils using high-resolution light-sensing microscopy and scanning electron microscope, with the resolution of the biological fossils up to 2 mm. Integral analysis of unmerous borehole loggings and three-dimensional seismic profiles laids a reliable foundation for revealing the internal architecture of the reef-shoal complexes. A detailed investigation was carried out on a total of 26 outcrop sections along the northern margin of the Tarim Basin. The contents of microelements like Sr, Ba and B in the pores of more than 100 samples were obtained via application of electronic probe techniques. The relationship between the uniform temperature and the salinity of hot-water calcite in the reef-shoal complex was analyzed based on the inclusion testing technology. The methods mentioned above complete the study on the control factors on the development of the reef-shoal reservoirs.

4. Ordovician Reef Biocenosis and Composition

Reef is a kind of submarine topography forming from local growth and accumulation of reef organisms [32]. In the geohistory there were a variety of reef organisms, which might be monotonous stromatolites cryptomonas, or calcareous alga, or might be complex ecosystems jointly forming from algae with a high disparity and abundance and metazoan. The Ordovician bioherm limestone was mainly discovered in the Yijianfang Formation of the Middle Ordovician and the Lianglitage Formation of the Upper Ordovician (Figure 2). The main fossil categories include thallophytes, calcareous alga, kaliapsidae, receptaculites, corals, stromatoporoids, bryozoans, brachiopods, trilobites, cephalopods, bivalves and echinoderms [33–36]. Webby [37,38] made a comprehensive discussion on global Ordovician reefs and divided them into five types, namely framework reefs, reef mounds, lime-mud mounds, microbial mounds and layered reefs. Accordingly, the reefs forming in the Ordovician system of the Tarim Basin may be divided into framework reefs, reef mounds, algal mounds and mud mounds, and their basic characteristics are listed in Table 1.

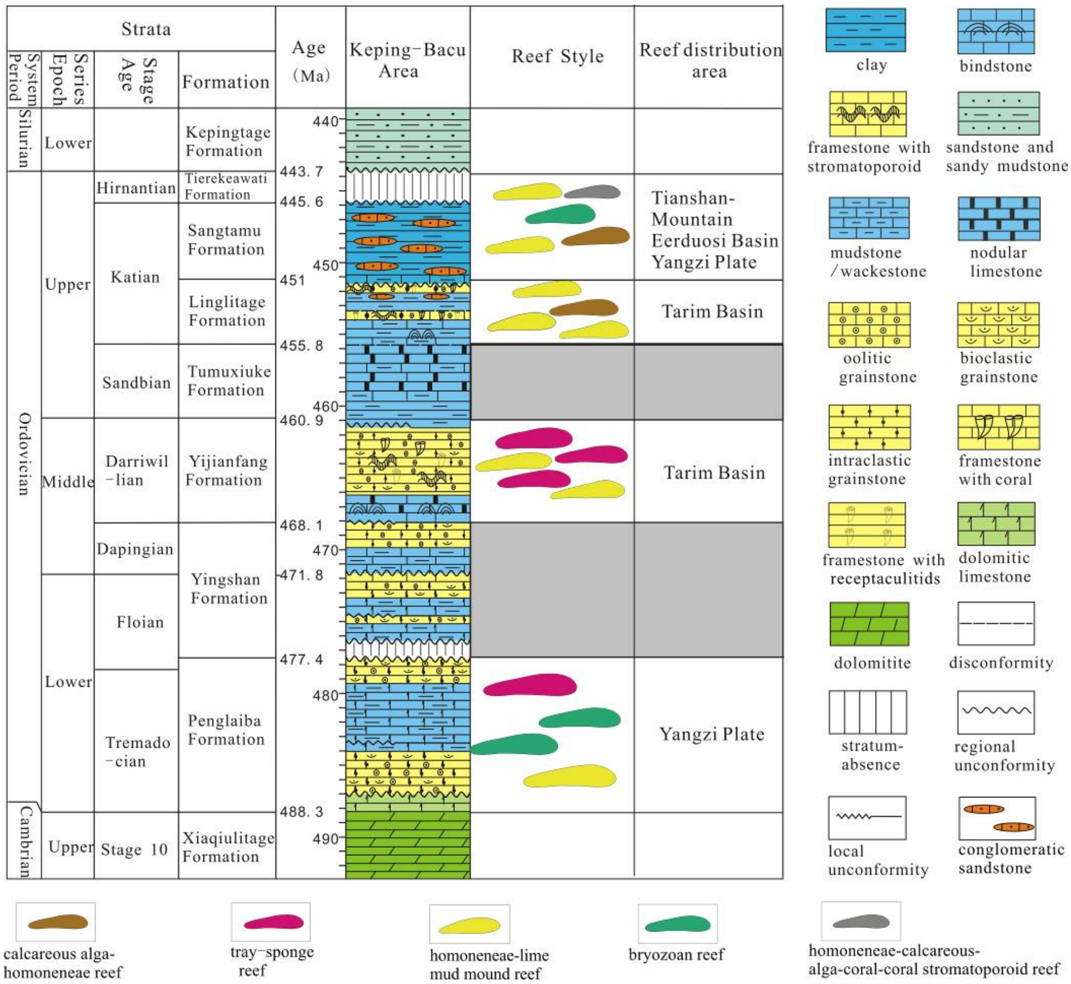

Figure 2. Ordovician Sedimentary Sequences and Distribution of Reefs in the Tarim Basin.

Table 1. Reef Organisms in the Middle and Late Ordovician Reef—shoal Complexes in Tazhong Area.

Reefs or Mounds	Reef Biocenosis	Sedimentary Characteristics
Framework reefs	Corals, bryozoans, stromatoporoids baffling communities, calcareous sponges, bryozoan baffling community	Mainly frame baffles forming locally, then lime and mud, and filled with a small amount of framework detritus and internal detritus
	Corals, bryozoans, vermiporella, Haide algae baffling community	
Reef mounds	Corals, stromatoporoids, codium, solenopora baffling-Girvanella-bind community	Cryptomonas as well as lime and mud accounting for more than a half, mainly the bind lime and mud, with rich detritus
	Cryptomona-bind corals, stromatoporoids, bryozoans, Haide algae baffling community	
	Stromatoporoid-cryptomonas stromatolites-bind community	
Algal mounds	Cryptomonas, Girvanella-bind-Haide algae, vermiporella, solenopora baffling community	Mainly binds, small sized calcareous alga framework, with rich bioclastics.
	Girvanella-bind bioclastic oncolite community	Mainly thallophyte bind lime and mud, with rich bioclastics.
	Girvanella-bind community	
Lime-mud mounds	Girvanella, cryptomona- stromatolites-bind nephrocytium sp community	Thallophyte-bind lime and mud with formation of birdeye and geode, most of ostracoda are intact, and others are broken.

The reefs discovered in the Lianglitage Formation of Late Ordovician in the basin, are mainly recognized in terms of the reef biocenosis such as the stromatoporoid communities. The biological fossils in the Formation are commonly more abundant than those in the Yijianfang Formation. The coral-stromatoporoid biocenosis of the Late Ordovician in the Tazhong uplift is the earliest coral reef discovered so far in China, and this is of important biological significance. Other symbiotic fossils include thallophytes, calcareous alga, foraminifera, sponges, bryozoans, ostracods, trilobites, gastropods, brachiopods and echinoderms (Figure 3). The specific characteristic of the reef paleoecology in the Lianglitage Formation of Tazhong Area is the diversity of the fossils, especially rich in thallose, calcareous alga and bryozoans, while there are relatively few species of coral-stromatoporoid in the framework reefs.

Corals identified in the framestones include tabulata and monomerous tetracoralla. Tabulata has no monomers and all of them are of complex. The identifiable genuses include Tetradium, Heliolites, Syringopora, Chaetites (Chaetetid, had been classified as Hydrozoa, and now as Tabulata in most cases), Amsassia, Catenipora, and Pachyporidae. Tabulata is mostly distributed in part of formations where grainstone is abundant. According to existing observation results, they are relatively concentrated in some horizons. Bryozoans debris and a small amount of brachiopod debris are partly distributed densely. Tetradium is a category with the highest abundance, and its outer wall is often attached with original yew alga, and mud is with its inner wall. There is much interspace in the coral framework, forming the shelter space, which provided conditions for the accumulation of mud. If the coral debris was accumulated not fast enough, the space might be partly or fully filled with mud and alga. The space between coral frameworks might be filled with bioclastics like bryozoon and small, thin-walled ostracods. Occasionally, calcareous alga clusters can be seen as attached to coral branches. The quick accumulation of gastropods, brachiopods and ostracod detritus as well as part of mud might bury and prevent the further growth of coral framework.

Another important bio-framework is sponge, including stromatoporoids, lishistid sponge and so on. Studies show that stromatoporoids involved in reef building in Tazhong area include Labechia, Labechiella, Tuveichia, Cryptophoragmus, Rosennella and Ecclimadictyon. Stromatoporoids are limited in number and species, but they are intertwined with other reef organisms, forming a solid biological skeleton. Observations suggest that small biocoenosis succession can form between stromatoporoids and stromatolites. In the reef-shoal deposits, the complete reservation of stromatoporoids framework can cause the formation of partial overburden rock. Calcareous sponge framework is more common, but the well-preserved drilling core samples are of lack. The spicules under plane aggregation and the scattered ones can be observed from the slices, and their category is hard to be identified.

Thallophyte is the main builder of lime-mud mounds bondstone and stromatolites, and also the key component of the oncolite beach and bioclastic beach near reef mounds. The identifiable genuses include Girvanlla, Nuia, Epiphyton, Renalcis (nephrocytium agardhianum) and so on. In addition, many algas can be observed, such as abundant chlorella alga and codium within the category of green alga as well as solenoporaceae and corallinaceae within red algas. As for the calcareous algas, they are mainly reserved in the algalclastic form, most of which can be found in the bioclastic-algae—a wackestone or grainstone, and the associated bioclastics mainly include echinoderms, ostracods and gastropods.

On the northern margin of the Tarim Basin, there are reef organisms and new point reefs with small-scale receptaculitidae-sponges and thalloses of the Middle Ordovician, which indicates that the Tarim plate had reef-forming paleogeography, paleoclimate and paleoecology environment in the Ordovician. For the reef biocenosis like corals and stromatoporoids in the Lianglitage Formation of the Upper Ordovician within Tazhong uplifts, the biological fossils are richer than those in the Yijianfang Formation, and they are China's earliest reefs discovered by far, filling in the gap of China's reefs of Late Ordovician. Especially, the abundance of thallophytes, calcareous alga and bryozoans is significantly higher than that of reefs of the Late Ordovician in other areas of China.

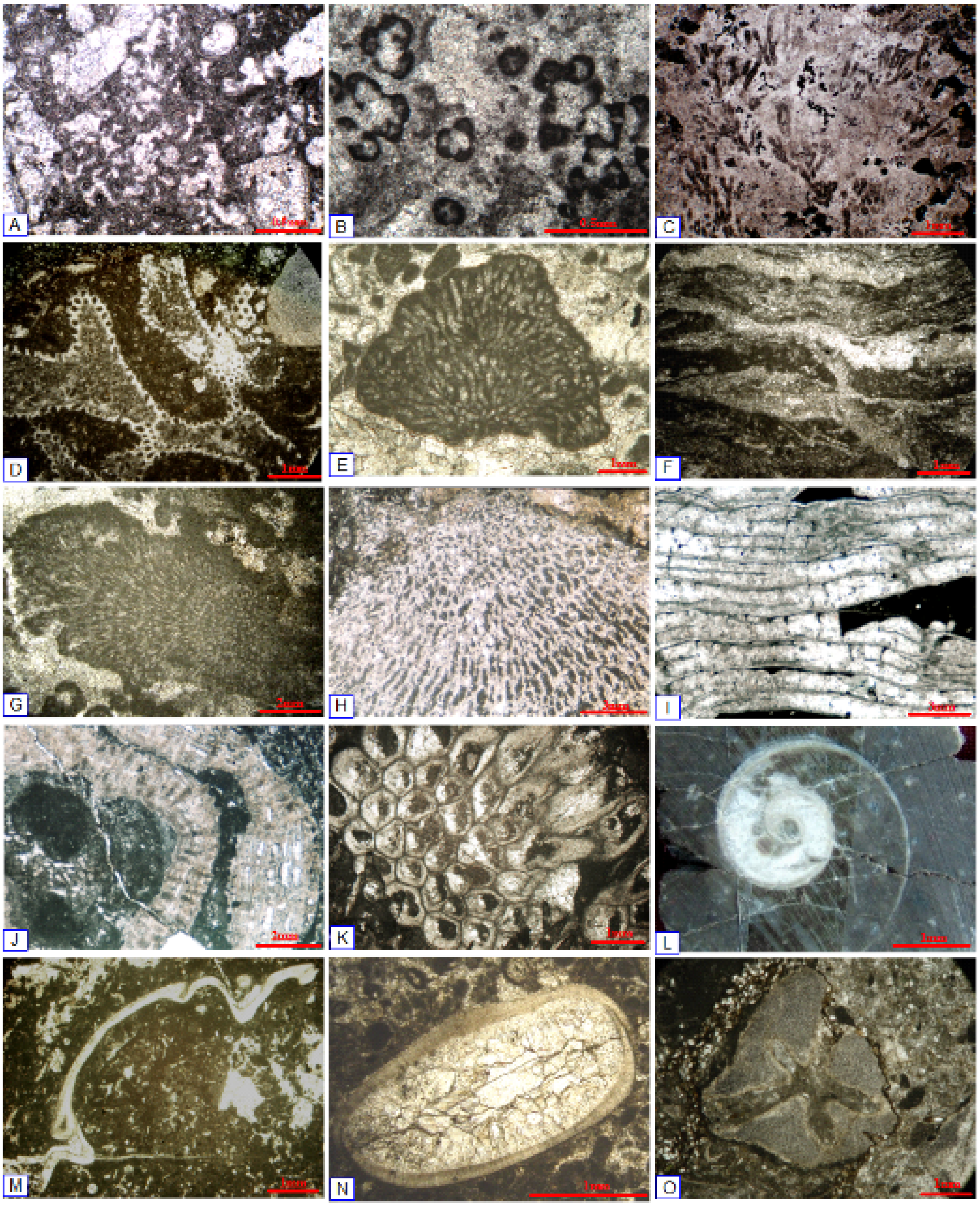

Figure 3. Types of reef biological fossils in Lianglitage Formation of Tazhong Area. (**A**) Girvanella; (**B**) Renalcis; (**C**) Epiphyton; (**D**) Verminopora; (**E**) Hedstroemia; (**F**) Sphaerocodium; (**G**) Solenopora; (**H**) Calcispongea; (**I**) Tetradium; (**J**) Stromatopora; (**K**) bryozoan; (**L**) bryozoans fossil; (**M**) trilobite fragments; (**N**) Ostracoda; (**O**) crinoid ossicle transection.

5. Architecture of Reef-Shoal Complexes

5.1. Depositional Facies and Lithofacies Associations of the Reef-Shoal complexes

The Ordovician reefs in the study area are often symbiotic with bioclastic shoal, and these complexes constitute one of the most important oil and gas reservoirs. The reef-shoal complexes are generally composed of massive receptaculitidae-sponges framestone, stromatoporoids framestone, coral framestone, algae-bind bioclastic grainstone and algae-bind psephitic grainstone, and they formed usually along the carbonate platform margin.

According to the analysis on the field and drilling core data, the carbonate deposits along the Middle and Upper Ordovician carbonate platform margin in the Tazhong area can be divided into three main rock types: (1) biohermal limestone; (2) grainstone or packstone; (3) wackestone and lime mudstone or mudstone. The biohermal limestone includes framestone, bafflestone, bindstone and cryptophyta limestone. The grainstones or packstones includes algal psephitic grainstone, bioclastic grainstone, algal grainstone, oolitic grainstone, algal packstone, bioclastic packstone, pelletal packstone or packstone. The wackestone includes bioclastic wackestone or pelletal wackestone. Based on the sedimentary facies sequence, they can be divided into subfacies and microfacies such as reef mound, lime-mud mound, grain clastic shoal and interbank sea. Different types of sedimentary microfacies consist of different rock types and lithofacies associations (Table 2), reflecting the differences in reef organism and sedimentary environments.

Table 2. Sedimentary Facies of Middle and Late Ordovician Reef-shoal Complexes in Tazhong Area.

Facies	Subfacies	Microfacies	Summary of Lithologic Characteristic
Facies along the platform margin	Reef mound	Reef core	Light gray thick massive sponges, corals, stromatoporoids, solenopora framestone, often sandwiched with reef breccia and biological psammitic-psephitie grainstone and rudstone representing channel sendiment
		Reef flat–reef cover	Gray to light gray thin to medium layered algae bindstone, grainstone containing oncolites, sometimes sandwiched with framestone
		Reef wing	Gray medium-thickness massive algal bindstone containing oncolite.
	Lime mud mound	Mound core	Medium-thickness massive cryptophyta packstone, cryptophyta grainstone
		Mound wing	Medium-thickness packstone, pelletal packstone with bind structure, containing bioclastic wackstone
		Mound flat	Gray medium-thickness layered algae bindstone containing oncolites to oncolites psehpitie grainstone
	Grain-clastic shoal	Bioclastic shoal	Gray and light gray medium-thickness grainstone and packstone, bioclastic packstone.
		Bio-calcarenite shoal	Gray and light gray grainstone and packstone, and psehpitie grainstone
		Calcarenite shoal	Gray and light gray layered bioclastic grainstone and packstone
		Oolitic shoal	Light gray medium-thickness oolitic grainstone. and packstone
	Interbank sea		Gray to dark gray packstone, containing bioclastic argillaceous packstone.

5.2. Analysis on Outcrops of Reef-Shoal Complexes

The field Ordovician reef-shoal complexes in the Tarim Basin are distributed in Section of the Yijianfang Formation in Bachu Yijianfang-Sickl-Keping area. In Yijianfang area, a total of 90 reef-shoal complexes in different scales have been discovered, twenty of which are large-scaled (more than 10 m × 5 m). The Yijianfang reef-shoal complexes formed within the range of 10~30 m under the purple limestone of the Tumuxiuke Formation. The reef-shoal complexes on the section are lenticular, with cellular characteristic, and their color is lighter than that of surrounding rocks. Besides, they are vertically presented as the lithological association from grainstone, framestone to bioclastic grainstone; and latterally, the framestones pass mainly into bioclastic grainstones, with a larger thickness and long extension (Figure 4).

The reef-shoal complexes can be divided into a number of microfacies, such as reef base, reef core, intra-reef shoal, reef flat, reef cover and reef flank. The reef flat, reef cover and reef flank are mainly composed of micritic crinoid limestone. The reef core consists mainly of framestone, bafflestone and bindstone. The reef-shoal complexes display obvious cycles in the vertical section; various microfacies repeatedly occur in the sequences; and from the spatial point of view, they have big-shoal and small-reef characteristics apparently (Figure 4).

After tracing outcrops, it is found that the sedimentary facies associations of these reef–shoal complexes from the inside to the outside of the platform margin may be divided into three zones: (1) the platform margin is the intensive formation area of reef-shoal complexes,with more baffle-reefs in large scale, and the reef base and platform margin shoal therein have a large thickness, long extension and good lateral continuity; (2) the area in the immediate vicinity of and inside the platform margin is the formation sub-zone of reef-shoal complexes, with less baffle-reefs scattered in small scale, and the reef base and platform margin shoal therein have a small thickness and short extension; and (3) the area far away from and inside the platform is the zone where baffle-reefs didn't form.

Figure 4. Formation Characteristics of Reef-shoal Complexes on Bachu Outcrop Section (The location is shown in Figure 1).

5.3. Structural Pattern of Seismic Sedimentary Facies of Reef-shoal Complexes

The analysis on drilling and seismic data indicates that the reef-shoal complexes forming along the margin of the Middle and Upper Ordovician carbonate platform of Tazhong Slopebreak I, is large-scaled and widely distributed. The thickness of single reef-shoal complexes is within 20 m to 70 m. And even, the one in the Tazhong Well 44 is up to 120 m. Many cycles occur vertically in the reef-shoal complexes, with the total thickness of 100 m to 300 m. In the perpendicular direction, there are mainly thin layers of reef bank and bioclastic bank which are stacked, showing a complex appearance. Inside the margin of the platform (e.g., Tazhong Wells 12 and 80) there are mainly interbank sea entraining bioclastic shoal, and reef mound sediments. As the reef-shoal complexes formed relatively late, they are located in the upper formation. The sedimentary units outside the margin of the platform mostly experienced 3 to 5 formation periods, and they have a larger thickness and scale (Figure 5). These reef-shoal complexes are distributed along the zone outside the margin of the platform, trending from NW to SE, with a wide range of lateral extension. The reefs in the Well Tazhong 62, for example, extend for 20 km from MW to SE, and their width is 1 km to 3 km in the NE to SW direction (Figure 6).

The comparison and analysis relative to domestic and foreign Late Ordovician reefs suggest that the reefs along Tazhong Slopebreak I are in a large scale. Based on previous worldwide discoveries and reports regarding Ordovician reefs, the Ordovician reefs are mostly patch reefs in a small scale, with the thickness of about 1 m to 30 m, and the maximum diameter ranging from several meters to 100 m or so [39–41]. The Middle and Upper Ordovician reef organisms along the margin facies zone of carbonate platform of Tazhong Slopebreak I are rich in species, including framework-building organisms and bonding organisms. In the Lianglitage Formation, the biological content is high, reaching about 30% to 70%, and plenty of bioconstructed limestones are contained therein. At that time, the platform might be subject to destruction and screening of strong winds and waves, which was conductive to the formation of bioconstructed limestone. Perhaps these conditions directly resulted in the formation of widely-distributed and large-scaled reef-shoal complexes.

Based on the comprehensive analysis on lithology and lithofacies of single well, along with the analysis and interpretation on the seismic sections in terms of seismic facies, type of sedimentary petrology and type of sedimentary facies, the seismic-sedimentary model of reef-shoal complexes may be established (Figure 7). The seismic reflection characteristics of the reef-shoal complexes of the Lianglitage Formation in Tazhong Area mainly include medium to weak amplitude, mounded reflection and blank reflection. Micritic limestone showed characteristics of moderate to high amplitude and parallel to sub-parallel seismic reflection. Through the comparison to inter-well reef complexes, it has been found that the reef mound is laterally weak in continuity, which is locally presented by positive uplifts, while the grain shoal has a good continuity. The reef-shoal complexes show such structural characteristics as multi-period stacking in the vertical direction and certain continuity in the horizontal direction.

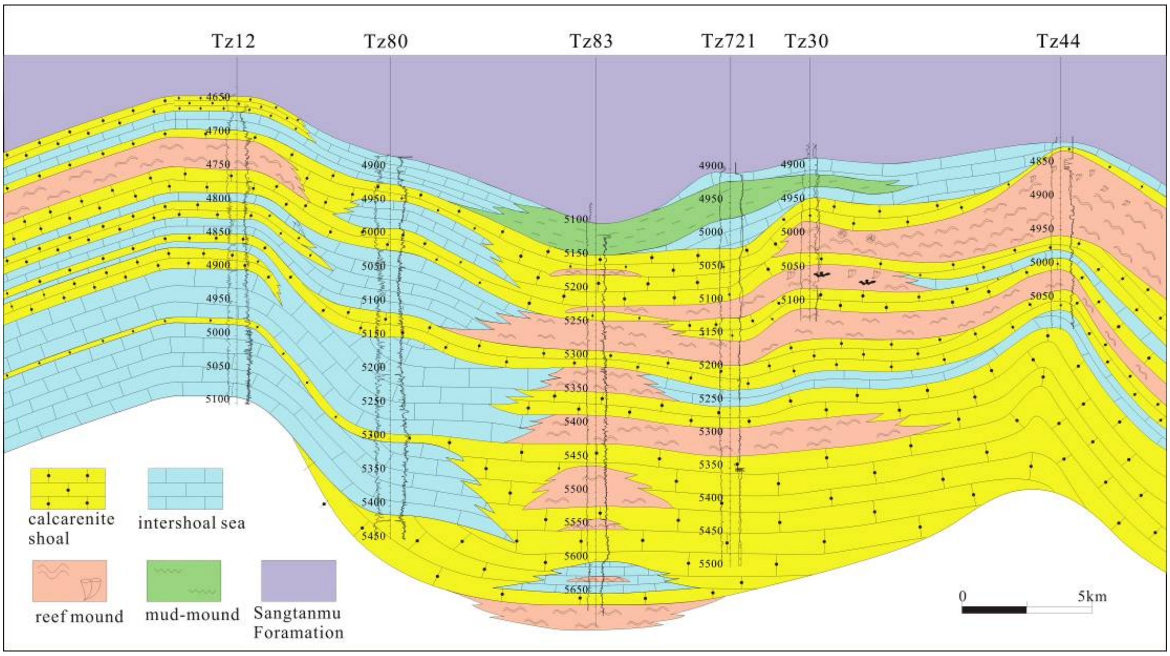

Figure 5. Geological Model for 3D Spatial Distribution of Reef-shoal Complexes in the Lianglitage Formation, Tazhong Area (The location is shown in Figure 1).

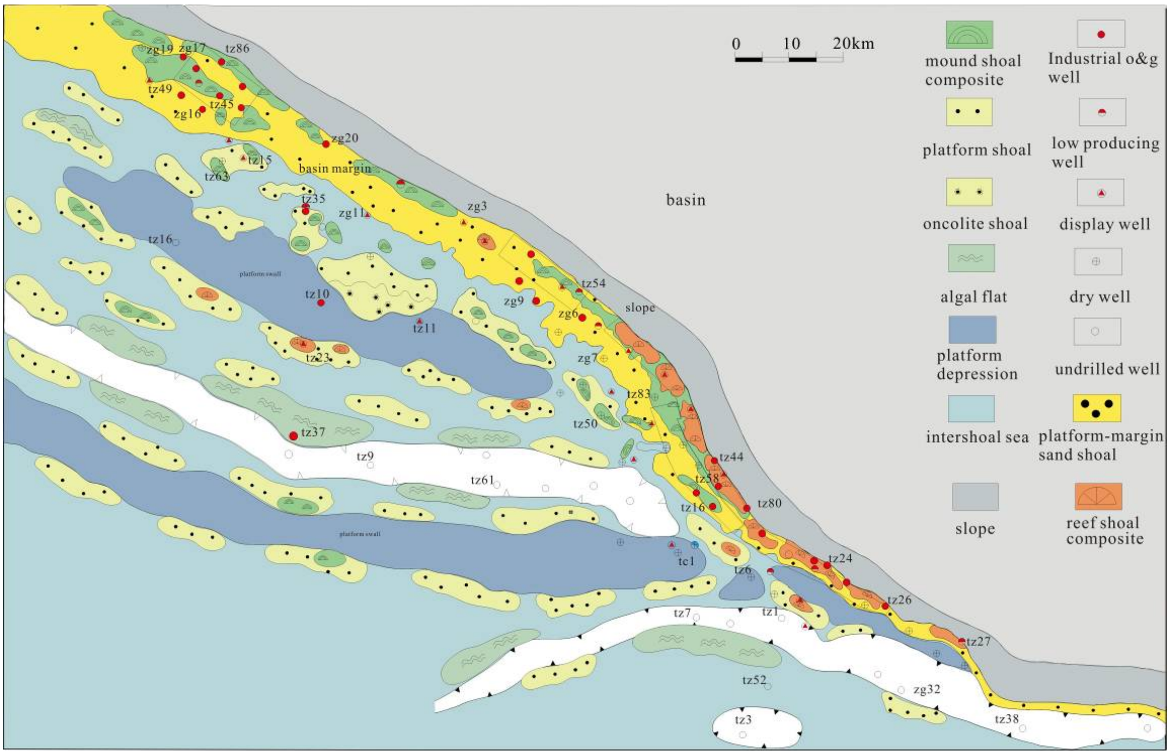

Figure 6. Distribution Map of Sedimentary Facies of the Lianglitage Formation (Upper Ordovician) along Tazhong Slopebreak I.

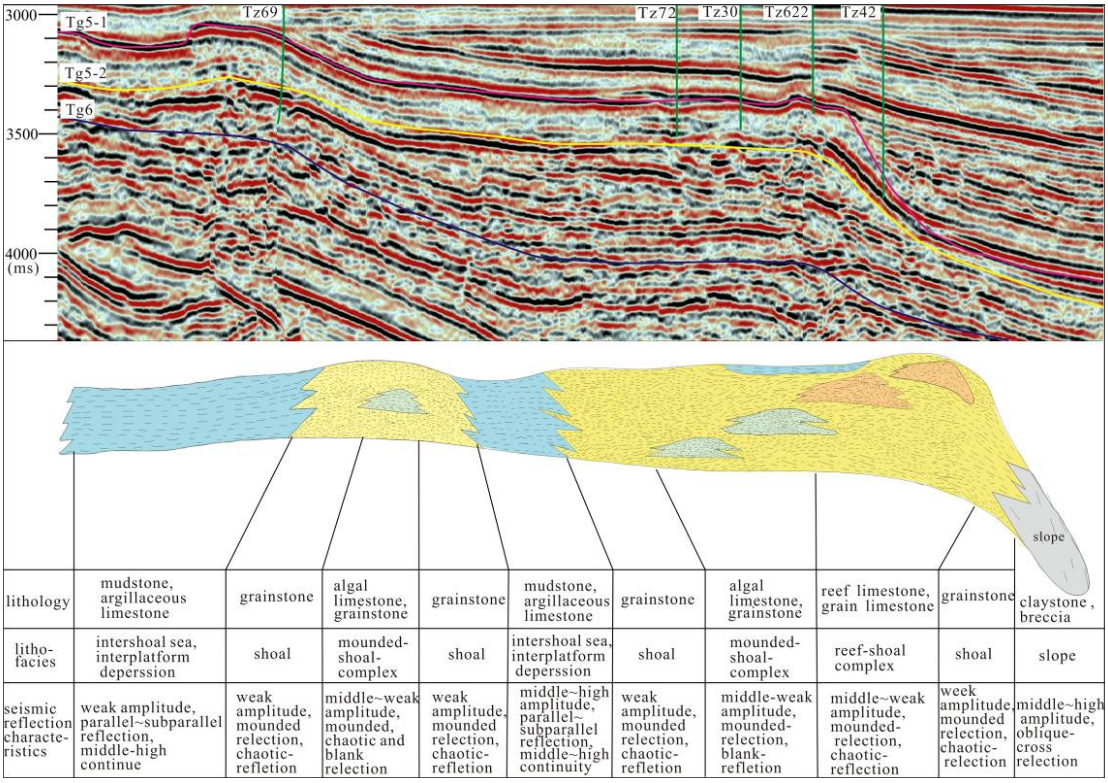

Figure 7. Sedimentary Distribution and Seismic Facies Characteristics of Reef-shoal Complexes of the Lianglitage Formation (Upper Ordovician) along Tazhong Slopebreak I (The location is shown in Figure 1).

6. Factors Affecting the Formation of Reef-Shoal Complexes Reservoirs

6.1. Leaching of Meteoric Water during Short-Term Exposure

In the Middle and Upper Ordovician reef-shoal complexes, a series of high-frequency cycles reflecting high-frequency changes of sea level (meter-level) can be identified. According to the comparison of the thorium/potassium ratio for Tazhong Well 62, combined with the study on the core and conventional logging data, it is found that the Ordovician carbonate changes significantly in meter-scale cycles. The thickness of an individual cycle among these high-frequency cycles is 2~4 m, showing a good correspondence to the meter-scale changes in reservoir physical properties, and the quality reservoirs mainly form in the shallowing upward meter-level cycles from the sea level. Of all the seven cycles identified in the Lianglitage Formation, those that are near the three sea-level falling period are found to be quality reservoir formation sections, and the exposed surfaces of the three periods formed three sets of quality reservoir sections (Figure 8). In the Late Ordovician, the Tarim Basin was in the transitional period from the passive continental margin to the active continental margin, so structural change and sea-level oscillation were frequent, which resulted in the multiple sedimentary cycle stacking. Due to the control of sea level changes, the shallow-water sedimentary units like bioclastic shoal and reefs formed commonly at the margin of the platform. In the regressive sedimentary sequence, accompanied by a temporary sea level relative decline, the deposits may be exposed above the sea surface or in freshwater lens. In the humid and rainy climate, the selective and non-selective dissolution may occur due to the leaching of the meteoric water with abundant CO_2, which resulted in the formation of various porosities with different sizes and shapes, thus transforming the reservoir quality and connectivity [7,16,42–44].

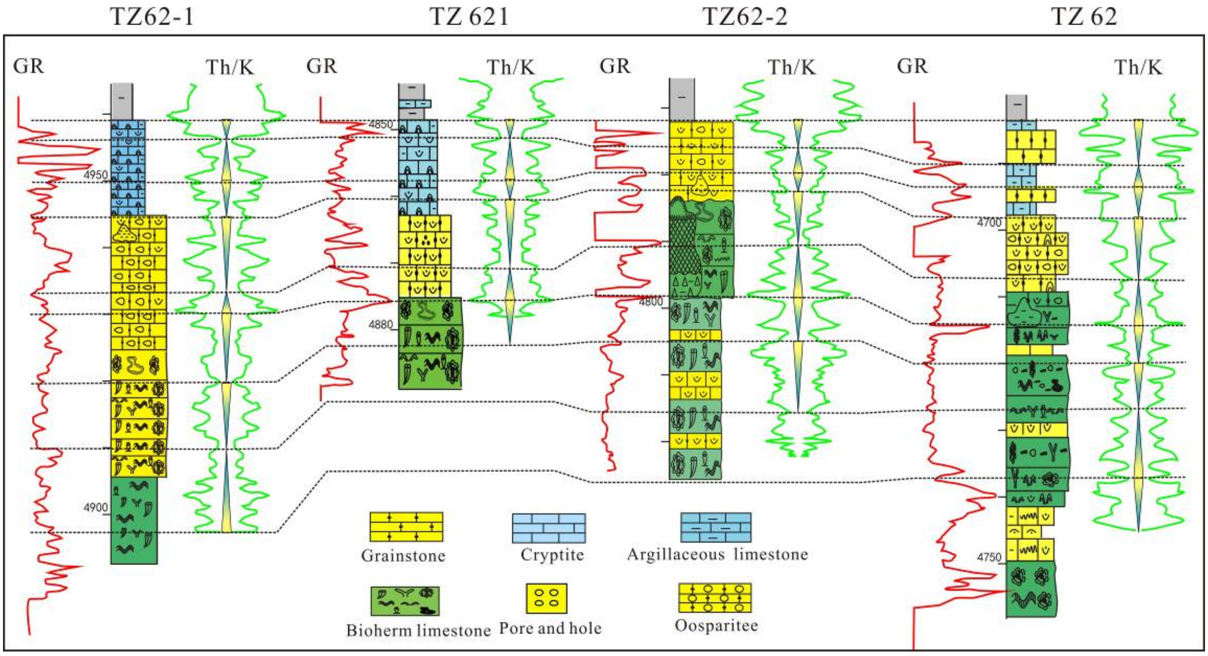

Figure 8. Correlation of High-frequency Cycles and Reservoir of Reef-shoal Complexes in Tazhong Well 62 (The location is shown in Figure 1).

6.2. Epigenic Karstification at the End of Sedimentary Period of the Lianglitage Formation

The epigenic karstification along the relatively long exposure surface might play an important role in the reformation of reef facies reservoirs along the Ordovician carbonate platform margin. It is found that a significant exposure might occur at the end of sedimentary period of the Lianglitage Formation along Tazhong Slopebreak I and karst caves in different sizes formed due to the epigenic karstification. Karst caves are mostly filled with gravels, mud, carbonate detritus and calcite. For example, during the drilling of Tazhong Well 62-2, a karst cave up to 10 m high were encountered, and the cave top was filled with brown gray columnar calcite crystal beams and brown giant crystal calcite, and where, intercrystal corroded cavities formed as well. The middle part of the cave was filled with solution breccia, which includes biological psammitic-psephitie calcarenite and sponge reef limestone. The space between solution breccia was filled with giant crystal calcite. The lower part is the dark gray mudstone containing breccia; and the upper part of the cave was semi-filled by half. The small and medium sized corroded cavities of the Lianglitage Formation are distributed by layer, with the thickness range of 0.8~20 m. They are less filled with debris and mud, and the reservation conditions are good. Through the analysis on the trace element B of the muddy filler sample for the cavities of typical wells, it is indicated that the content of the muddy filler B for the cavities is lower (Figure 9), with meteoric water origin.

6.3. Fault and Crack Effect

In Tazhong area, there are mainly three periods of faults, namely the fault parallel to Tazhong Fault I, forming in the Early and Middle Caledonian; the associated fault in north-west trending, parallel to Tazhong Fault I, forming in Late Caledonian; and the left-lateral slip fault in north-east trending from Silurian to Devonian, perpendicular to or obliquely crossing Tazhong Fault I [45–49]. The late slip fault crosses the previous main fault and associated fault. The tectonic fracture and the generated cracks have a significant influence on the reservoir performance. Cracks play a significant role in connecting the pores and improving the permeability of reservoirs. Besides, they are also conductive to the movement of pore water and groundwater as well as the formation of dissolved cavities, which may significantly improve the reservoir performance. The zone immediately outside the platform of Tazhong Fault I is intensive in this point, and a number of high-angle fractures, obliquely crossing fractures and mesh fractures were formed. The acidic water entering the fractures can promote burial dissolution, thereby, the dissolved fracture, beaded dissolved pore and dissolved cavities. Statistical analysis shows that this effect can increase the porosity by about 2%, so that a new combination of reservoir permeability along with the early residual cavities would form.

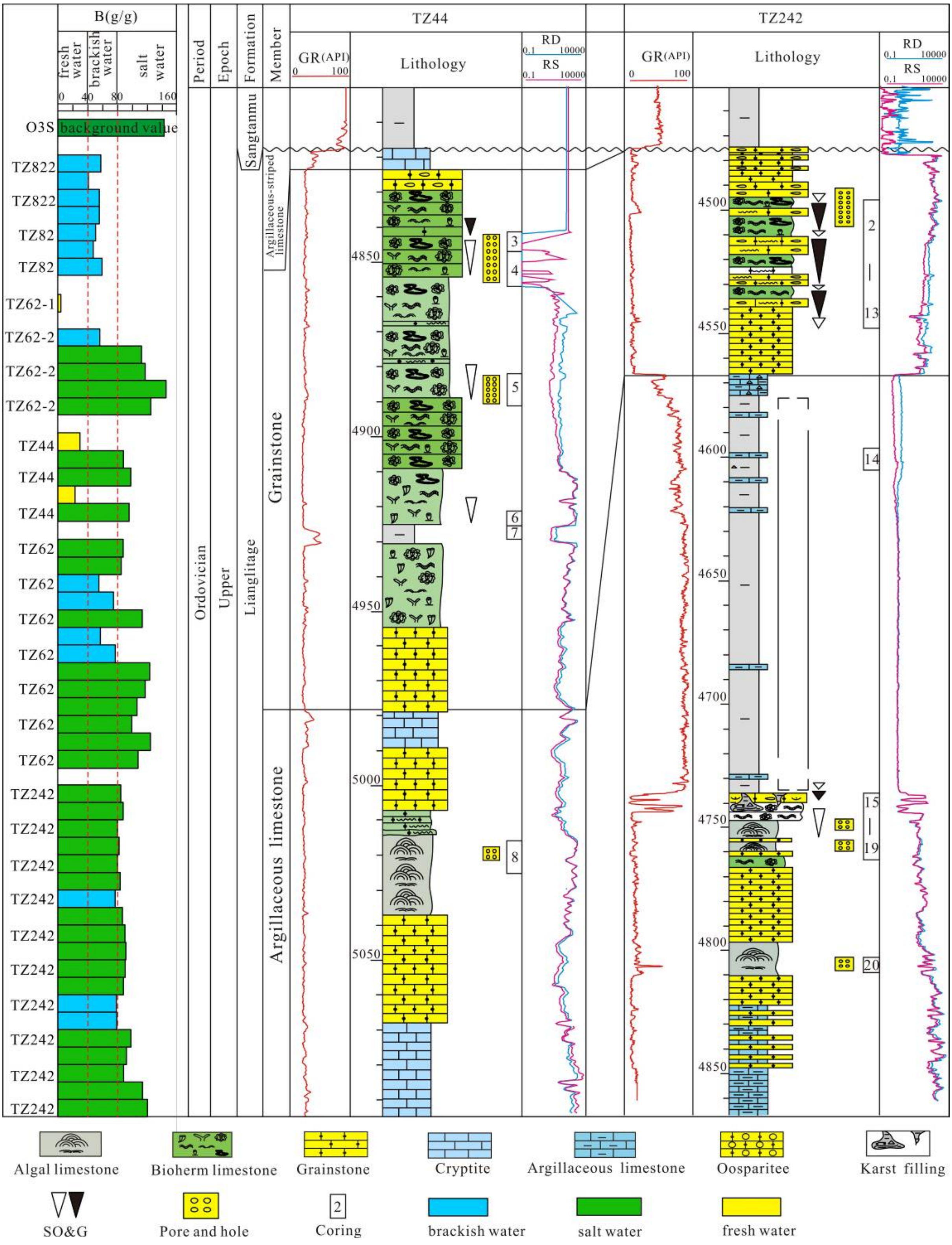

Figure 9. Distribution of Muddy Filler B for Cavities of Reef-shoal Complexes in Tazhong Area (The location is shown in Figure 1).

7. Conclusions and Discussion

(1) The main reef-forming organism of the Middle and Late Ordovician reefs in the Tarim Basin are receptaculitidae-sponges, corals and stromatoporoids, with a large number of symbiotic fossils species, especially thallophytes, calcareous alga and bryozoans. The coral-stromatoporoid reef biocenosis of the Late Ordovician in the Tazhong uplift area is the earliest coral reef discovered so far in China, which may belong to the world's largest reef groups of the Ordovician.

(2) The Middle and Late Ordovician reefs in the Tarim Basin are actually reef-shoal complexes, including the massive framestones forming from reef organisms, such as the receptaculitidae-sponges framestone, stromatoporoids framestone, coral framestone, and grainstones composed mainly of algae-bind grainstone, algae-bind psephitie grainstone. And they are featured as “big shoal and small reef”. The reef-shoal complexes are stacked vertically and horizontally, and often show shallowing upward sequences.

(3) The reef-shoal complexes were improved by leaching of exposed meteoric water, thermal fluid reformation and tectonic fracture, so large-scales reef-shoal complexes comprise quality reservoirs. The single reef-shoal complex is generally of large thickness and many depoditional cycles. The reef-shoal complexes are usually distributed and extended as clusters or zones along with the platform margin, with a length up to 200 km from the west to the east along Tazhong Slopebreak I, and the width of 5~8 km from the south to the north, which comprise the most important zone for the formation of reef-shoal facies reservoirs.

The original contributions reported in this study are contained within the article. For further inquiries, please reach out to the corresponding author.

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Author Contributions

Conceptualization, L.Z. and H.L.; Data curation, L.Z. and H.L.; Investigation, H.L., L.H., and C.L.; Methodology, C.L. and L.Z.; Resources, Q.H., L.Z., and H.L.; Software, Q.H. and H.L.; Supervision, L.Z. and L.H.; Validation, L.H., and C.L.; Writing—original draft, H.L.; Writing—review and editing, Q.H. and Z.Z. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

Authors Liang Zhang, Li Huang, and Qiao Huang were employed by the Research and Development Center for Ultra-Deep Complex Reservoir Exploration and Development. The other authors confirm that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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