

Development pattern and reservoir-formation mechanism of reef-bank complex in Late Ordovician Lianglitage Formation, Tazhong area, Tarim Basin, China

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Received 12 January 2016 ; revised 25 May 2016

Present study consists the development pattern of reef-bank complex and its reservoir formation mechanism. The earliest Ordovician coral-stromatoporoids reef-building organisms are found in Lianglitage Formation, which fills the blank of Late Ordovician organic reef in China. Type of sedimentary microfacies, combination form and scale differentiation of reef-bank complex in Lianglitage Formation are controlled by high-frequency sea-level change and multi-stage tectonic evolution. In vertical direction, four or five periods of reef-back motivated inside out of platform margin of Lianglitage Formation. Besides that, reef-bank complex is linear and clumped distributed along Tazhong NO.1 fault belt on horizontal direction. High-energy reef-bank in platform margin controlled distribution of favourable reservoir lithofacies. Karstification in syngenetic-supergene stage is the key factor for the development of high-quality vuggy reservoir. Hercynian deep fluid that migrating along the faults, fractures and previous vuggy layers greatly improve the reservoir property of reef-bank carbonates during the buried process.

[Keywords: reef-bank complex, tectonic evolution, development model, reservoir formation mechanism, Lianglitage Formation, Tazhong area]

Introduction

As a special carbonate and complicated reservoir system, reef-bank complex is one of the main targets of global oil and gas exploration^{1, 2}. Ordovician period is the main depositional age for worldwide large-scale carbonates in epicontinental seas^{3, 4}. The submarine cementation damages seriously the effectiveness of primary pores of reef-bank carbonate rock during the post-depositional stage^{5, 6}. The reef-bank complex will easy to generate high-quality reservoir when it reworked by the karstification during the

penecontemporaneous to epidiagenetic stage, which caused by the physiognomic uplift of reef-bank and the frequently eustatic sea-level change⁷⁻⁹, and miscellaneous fluid-tectonic action during the buried process^{10, 11}. However, some differentiation and particularity of reef-banks exist in structure characteristics, sedimentary characteristics and diagenetic environment¹²⁻¹⁴. Therefore, research on growth, development and distribution rules of reef-bank complex in Lianglitage Formation is necessary in order to search the characteristics, distribution rules and

Formation mechanism of reef-bank reservoir.

Tazhong area is located in the middle part of the central fault belt of Tarim Basin, China¹⁵ (Fig.1). Thick reef-bank carbonates have been deposited in upper Lianglitage Formation in Tazhong area, range from 100 meters to 300 meters in the thickness, and are the main productive layers of several reef oil/gas fields of million-tons scale¹⁶. The complexity of reef-bank growth, evolutionary characteristics and reservoir genesis are controlled by the evolution process of rimmed platform in Tazhong Uplift^{17, 18}. Aiming at these tough issues such as large buried depth, complexity of underground structure, variety of biocomposition and biotype, complexity of spatially distributing and reservoir genesis of reef-bank carbonate rocks, scholars form home and abroad have conducted a series of studies and have made some significant progress^{6, 9, 11, 15-20}. Predecessors are restrained by inadequate core data and inaccurate interpretation of logging and seismic data, so the researches on reef-bank development pattern and reservoir formation mechanism are not sufficiently clear and detailed. To solve these problems, Based on the study of palaeontology, petrography, lithofacies sequences, and methods of fluid inclusion and electron probe testing, this paper researches the development pattern and reservoir-formation mechanism of Lianglitage reef-bank complex.

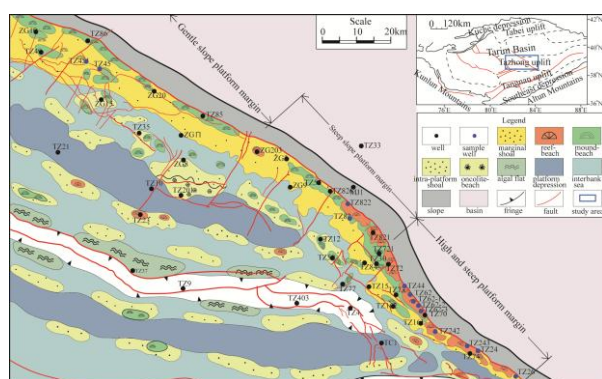


Fig.1 Overlap distribution map of the structure and sedimentary facies of Lianglitage Formation in Tazhong area

Materials and Methods

Rock constituents and paleontologic component in Lianglitage Formation are analyzed by the observation and description of 1000m cores from 18 wells and the identification of 320 thin-sections under the high-resolution light microscope and scanning electron microscope. The content of trace element of calcites filling 66 caves from 11 wells is obtained by the electron microprobe. The salinity and homogenization temperature of inclusion in cave-filling calcites are measured by the microscope with geology-type cooling-heating machine. All these results are used to complete the analysis of controlling mechanism of reef-bank reservoir. To ensure the representative and validity of the test result in Lianglitage Formation, the distributed uniformity from plane and vertical are both full considered, and all the testing data are obtained from Laboratory of Natural Gas Geology of Southwest Petroleum University, China. The content of trace element is measured by JCXA-733-type electron microprobe with error rate less than 2 percent. Salinity and temperature of inclusion are carried out with THMS600-type cooling-heating machine. Test results are shown in table 2 and table 3.

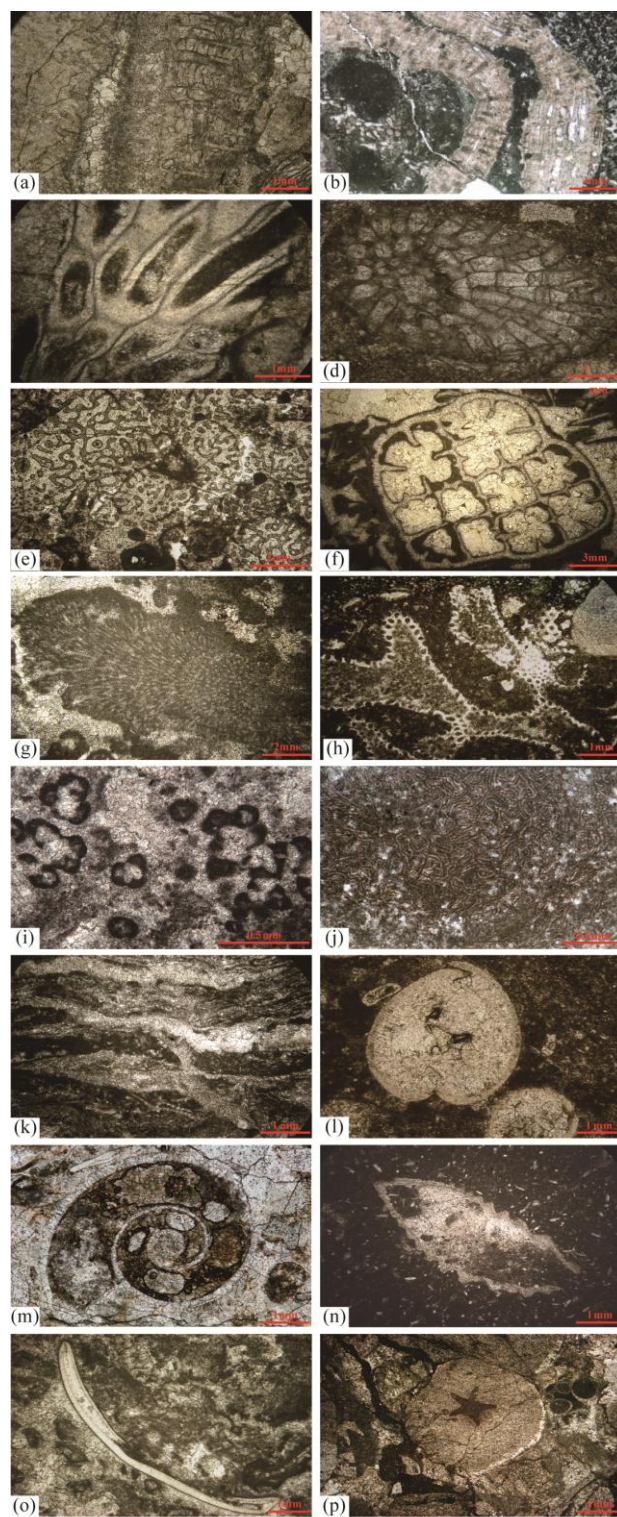
Results

The Late Ordovician is the main developing of reef-building organisms in geological history²¹⁻²⁵, in which period a wide variety of reef organisms have developed. Stromatolites cryptophyta and calcareous algae that from single category, biological component types fromed abundant high-disparity alga and metazoan, low-disparity animal, all above participate in organic reef-building. Based on the identification of cores and thin-sections from 18 wells in Tazhong area, the earliest Ordovician coral-stromatoporoids reef building organisms are found in Lianglitage Formation. A lot of reef category has been found in Lianglitage Formation, such as low thallogens,

calcareous algae, lithistidas, sponges, receptaculitids, corals, stromatoporoids, bryozoans, brachiopods, trilobites, cephalopods, bivalves and echinoderms. According to fossil content and reef-building function, reef-building organisms can be divided into four categories, which are frame builder organism(Fig.2a-b), baffler organism (Fig.2e-h), bond-crust organism (Fig.2i-k) and reef-adhering organism(Fig.2l-p).

According to the analysis of lithology and reef-building organism of Lianglitage Formation, growth cycle of single organic reef may be subdivided into five periods, which are foundation(Fig.3a), colonization(Fig.3b), breeding(Fig.3c), decline(Fig.3d) and reef-cap phases(Fig.3e).

Under the control of high-frequency sea-level change and tectonic subsidence, there are four or five periods of reef-bank developed vertically in Lianglitage Formation, and the single reef-bank complex ranges mainly from 20 meters to 70 meters in the thickness. On horizontal direction, the supermature zone of reef-bank is mainly present strip or patch shape, and it distributed along the platform margin facies belt which is head for NW-SE. However, the type and scale of sedimentary microfacies that controlled by tectonic action vary in different position of Tazhong NO.1 fault belt. Tazhong 24-44 wellblock located in the east of the fault belt, which belongs to the steep-slope platform margin, in which developing 3-5 sets of reef-bank complex, with great thickness, steep slope and narrowly lateral extension. The Tazhong 72-54 wellblock where located in the middle of the fault belt is high-steep-slope platform margin, in which developing 2-4 sets of reef(lime-mud mound)-bank complex. Compared with the steep-slope platform margin where in the east of the fault belt, the periods and thickness of lime-mud mound increase apparently, and sedimentary thickness is lesser while slope gradient is slower and lateral extension is wider.



(a)-tabulate coral, TZ242 well, 4517.30m, plainlight; (b)-stromatoporoid, TZ161 well, 4400.4m, plainlight; (c)-bryozoan, strip shape, TZ62 well, 4717.67m, plainlight; (d)-bryozoan, lamellar, TZ12 well, 4648.89m, plainlight; (e)- calcisponge, TZ826 well, 5672.83m, plainlight; (f)-Tetradium, quincunx, TZ30 well, 5067.60m, plainlight; (g)-Solenopora, radial filaments, TZ73 well, 4813.53m, plainlight; (h)-Vermisporia, cylindrical frond, TZ30 well, 4983.20m, plainlight; (i)-Renalcis, TZ822 well, 5856.59m, plainlight; (j)-Girvanella, TZ15 well, 4575.40m, plainlight; (k)-Sphaerocodium with laminated structure, TZ44 well, 4920.85m, plainlight; (l)-Ostracoda, TZ30 well, 4888.50m, plainlight; (m)-gastropod with grain texture, TZ12 well, 4392.85m, plainlight; (n)-Brachiopoda with leaf structure, TZ74 well, 4680.78m, plainlight; (p)-crinoid with intergrown crystal structure, TZ77 well, 4806.70m, plainlight;

Fig.2 Reef-building organisms of Lianglitage Formation in Tazhong area

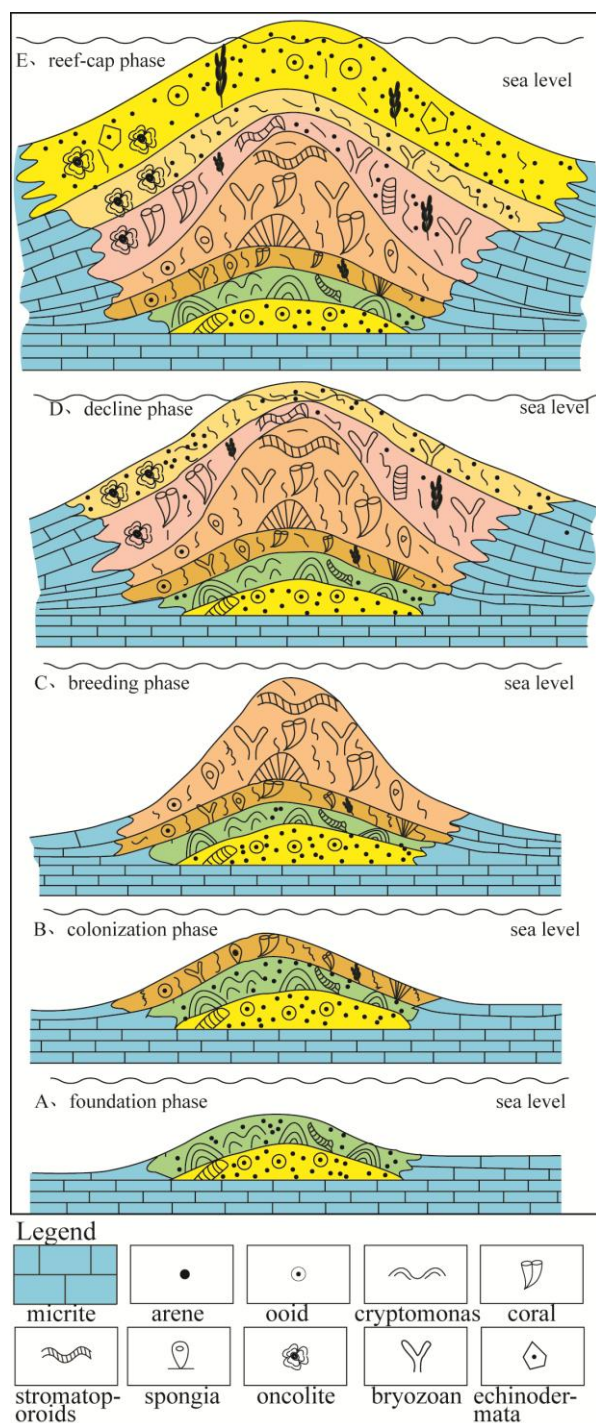


Fig.3 The growth cycle of single organic reef of Late Ordovician Lianglitage Formation in Tazhong area

The Tazhong 85-45 wellblock where located in the west of the fault belt is low-steep-slope platform margin in which developing 1-2 sets of lime-mud mound-bank complex, and the margin has the minimum sedimentary thickness and the most gentle slope with the most wide lateral extension (Fig.1).

Under the depositional background of global sea-level rising, tectonic intensity in Lianglitage Formation was gradually strengthening from top to bottom because of the regional tectonic extrusion and progradation of carbonate platform. The area suffered long-time erosion before the deposition of Lianglitage Formation, which formed karst palaeogeomorphology system with a feature of high in west and low in east, and the palaeogeomorphology during the Lianglitage depositional stage has the same feature. The sedimentary process of Fifth to First Members of Lianglitage Formation displays the transition from sea transgression to regression.

Low-energy carbonate sediments have been deposited in the Fifth and Fourth Members of Lianglitage Formation. Some isolated small-scale lime-mud mounds developed around the platform margin. Aggradation and retrogradation were shown on mound-bank facies with depositional pattern of deep in east and north, shallow in west and south (Fig.4a).

The Third Member of Lianglitage Formation deposited stably. Organic reef and lime-mud mound began growing in the platform margin and some small-scale lime-mud mounds deposited in open platform. Meanwhile, reef-bank and mound-bank obviously migrated to the outer belt of platform margin and aggraded vertically (Fig.4b).

The depositional period of the Second Member of Lianglitage Formation was the main developing period for reef-mound, and the two periods of reef-bank belong to vertical accretion deposit. Under the influence of tectonic extrusion, reef-bank complex migrated from the inner belt of the platform margin to the outer belt, meanwhile it showed linear distribution along the outer belt of platform margin (Fig.4c).

One or two stages of reef-bank complex have been deposited in the First Member of Lianglitage Formation. Under the influence of drastic tectonic compression, the depositional pattern presents a feature of uplifting in southeast

and plunging in northwest. As a whole, the regularly distributed from the outer belt to platform margin, and the reef-bank complex decreases gradually in the dimension(Fig.4d). To the end depositional period of Lianglitage Formation, the platform margin exposed and reformed by the karstification resulted from sea-level decline and tectonic uplift.

Several sets of reef-bank complex have been deposited in the platform margin in the study area during the Late Ordovician Lianglitage time, and all the single reef-bank complex are favorable reservoirs²⁶. The structure and lithology of Lianglitage carbonates are controlled by sedimentary microfacies, further control the development degree of primary porosity and affect the development of dissolved pore to a large extent. The existence of primary pore can provide the dissolution place and condition for the later dissolution. Result of porosity and permeability test of 60 Lianglitage limestone samples from 6 wells in the study area(Table 1) shows that reservoir property of grainstone is better than that of micrite, and the bioclastic bank and biocalcirudite bank microfacies developed in reef (mound)'s growing environment are the most favorable reservoir lithofacies while reef core microfacies and calcarenaceous bank microfacies followed, and the reservoir property of limestones deposited in low-energy environment of platform interior are the worst. Meanwhile, the palaeogeomorphic rise resulted from the growing of multi-stage reef-bank, which provides favorable conditions for the further corrosion. Thus, the distribution of favourable reservoir lithofacies is controlled by high-energy reef-bank in platform margin.

Controlled by the tectonic uplift and relative falling of sea-level, reef-bank complexes located in the depositional geomorphic high are easily to be exposed to meteoric freshwater diagenetic environment, and then corrode and reconstruct by freshwater riching in CO₂, thus forming various secondary pore spaces(Fig.5a-c).

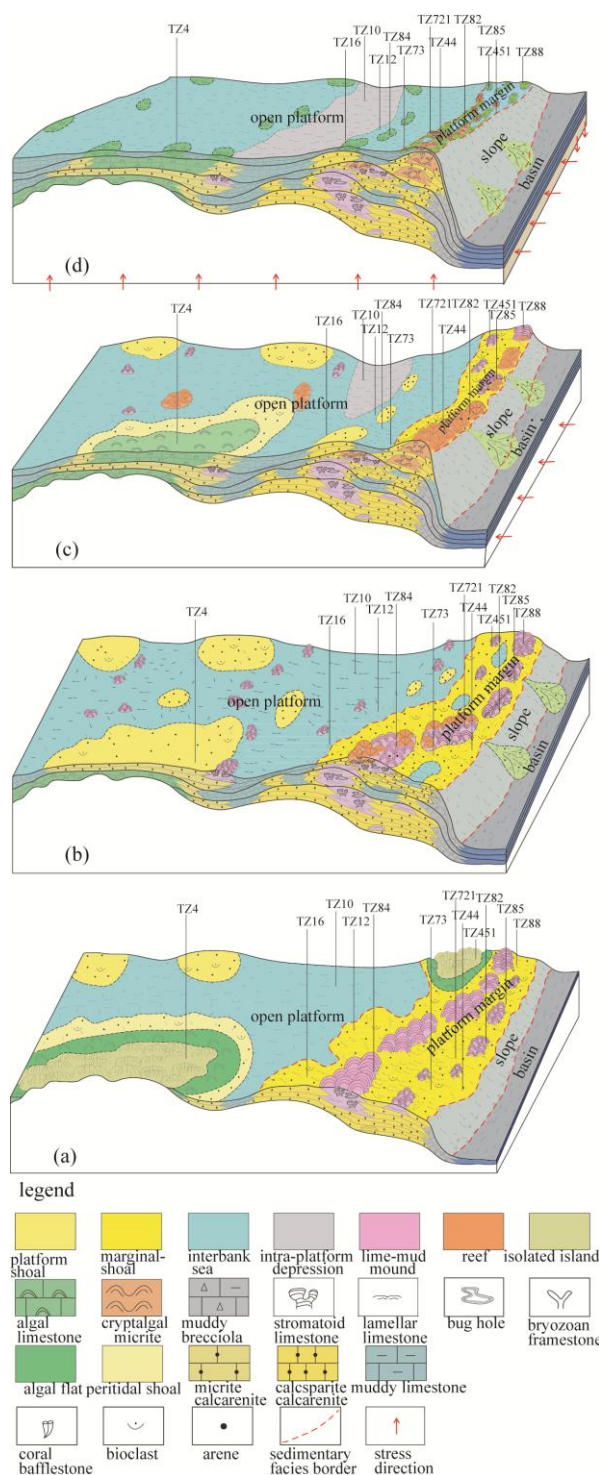


Fig.4 Block diagram showing reef-bank development model of Late Ordovician Lianglitage Formation in Tazhong area

Because of low salinity and early hydrocarbon injection in the depositional geomorphic high, early formed dissolution pores are saved, which improves property and

Table 1 Porosity and permeability of different lithology and microfacies samples in the Lianglitage Formation						
lithology	porosity (%)		permeability ($\times 10^{-3} \text{um}^2$)		microfacies	sample quantities
	average	range	average	range		
intraclastic and bioclastic grainstone	1.95	4.01-1.22	1.84	9.52-0.04	bioclastic and calcarenaceous bank	9
oosparite	1.82	4.12-1.02	1.43	9.91-0.08	high-energy oolitic bank	8
bioclastic limestone	1.78	4.25-1.03	1.21	8.76-0.05	bioclastic bank	8
bioclastic calcarenite	1.70	4.31-0.03	0.75	8.01-0.03	bioclastic and calcarenaceous bank	6
sparry calcarenite	1.42	4.53-0.02	0.44	7.11-0.02	high-energy calcarenaceous bank	7
micritic calcarenite	1.15	3.42-0.04	0.37	7.45-0.014	low-energy calcarenaceous bank	6
bioclastic bindstone, framestone	1.02	4.12-0.21	0.33	4.34-0.016	reef core	6
cryptalgalaminite	0.85	5.21-0.15	0.38	5.02-0.01	mound core	5
limestone	0.73	3.85-0.02	0.31	4.11-0.013	low-energy limestone	5

connectivity of reef-bank reservoir. On the contrary, controlled by lithology and high-salinity of the depositional geomorphic low, this area suffered intense atmospheric cementation and packing action, which made serious damage to reservoir property (Fig.6a). The development of multiphase meteoric freshwater dissolution in Third-First Member of Lianglitage Formation is

dominated by reef-building and high-frequency sea-level change. Therefore, many sets of high-quality reservoir are formed in the study area. The same exposure time can be formed by multiple exposure which caused by secondary sea level changes. Under the control of the fluctuate and migrate of multiple free surface, reef-bank carbonate at the same location get multiple reconstructed by early meteoric fresh water dissolution, and the reservoir property is improved further.

After Lianglitage depositional period, the tectonic uplift and relative falling of sea-level result in the exposure of carbonate platform, which turned sedimentary physiognomy into karst topography. Lianglitage carbonates are reconstructed by supergene karstification. A massive exposure occurred among the platform margin reef-bank of the higher karst palaeogeomorphology, while the exposure ranges water dissolution, and the reservoir property is improved further.

and times is limited in the low-lying places. The supergene karst system can be divided into surface, vertical vadose, horizontal underflow and deep sluggish flow karst zones in the vertical direction. Vuggy connectivity and validity are

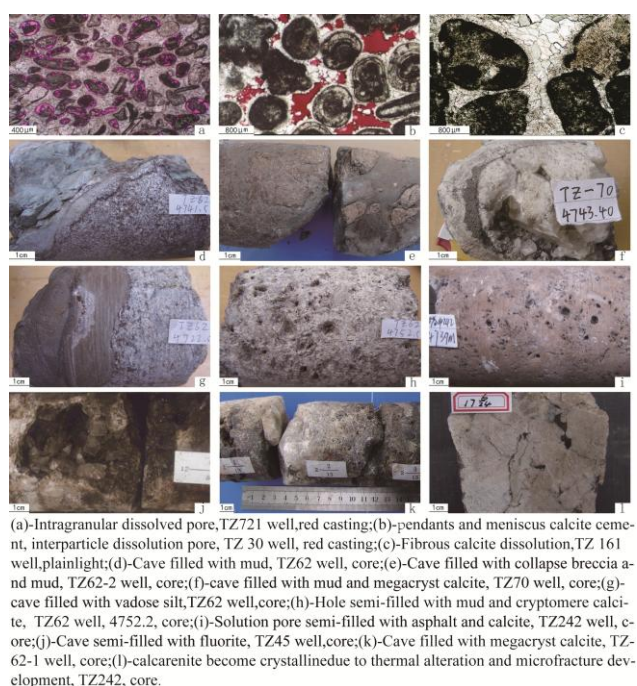


Fig.5 Characteristics of different karstification of Lianglitage formation in Tazhong area

pretty good in the surface karst zone as well as horizontal underflow karst zone, and porosity in these zones increase about 4%-8%(Fig.6b). Affected by multiphase relative sea level changes, high places of karst palaeogeomorphology intermittently exposed in meteoric freshwater environment, and because of the atmospheric fresh water dissolution, vertical vadose karst zone mainly developed the non-selective karren and pore, while the horizontal underflow zone mainly developed selective dissolved pore and cave. The dissolved pores are effective reservoir space, which has a great improvement to the capability of the reservoir.

The large caves and vugs on the top of Lianglitage Formation are filled with breccia, mud, carbonate fragments and calcite, however, vugs are less filled than large caves(Fig.5d-h). Analysis of the trace elements B testing data of 30 filling samples inside cave and vugs in 11 typical wells (Table 2) shows that cave filled with argillaceous is characterized by low B content which is distributing among 40($\mu\text{g/g}$) to 100($\mu\text{g/g}$). The B content of testing samples are much lower than the B content of mudstone in Sangtamu Formation(148($\mu\text{g/g}$)), indicated that all the testing samples are formed in the meteoric water environment. Tazhong 62-Tazhong24 well block that located in high karst geomorphology suffered strong supergene karstification. Many sets of vuggy layer with great thickness and good

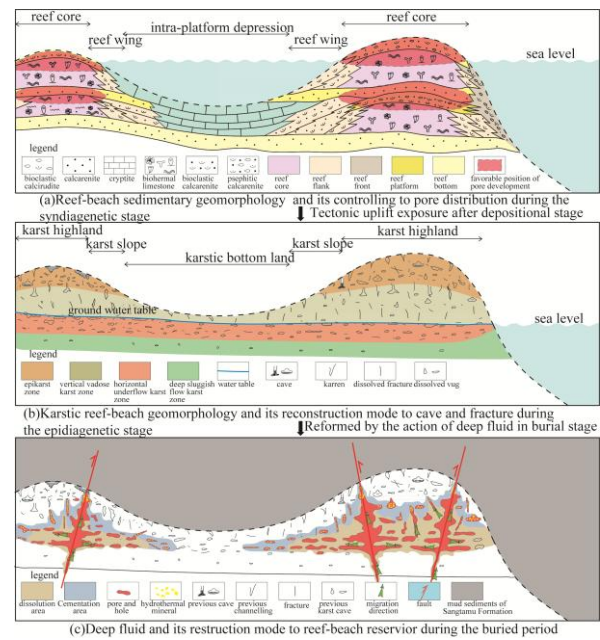


Fig.6 The different karstification of reef-bank reservoir reconstruction mode of Lianglitage Formation in Tazhong area

property are formed result from supergene karstification on the top of Lianglitage Formation.

Deep fluid that moved along fracture, unconformity surface and previous vuggy layers can corrode the carbonate near these channels(Fig.6c). This dissolution can form a large number of needle pores and small-size dissolution vuggy (Figure 4i). The deep fluid filling inside dissolution vugs and fractures can also precipitate out different types of mineral

Table 2 Boron content of testing data of argillaceous filling which filled inside-cave in Tazhong area

Well number	depth (m)	B($\mu\text{g/g}$)	Well number	depth (m)	B($\mu\text{g/g}$)	Well number	depth (m)	B($\mu\text{g/g}$)
TZ822	5612.5	60	TZ 62-3	5080.7	94	TZ 44	4889.7	86
TZ 822	5617.3	42	TZ 62-3	5082.2	91	TZ 243	4442.3	87
TZ 822	5643.7	57	TZ 62-3	5085.6	89	TZ 243	4447.1	88
TZ 822	5648.3	58	TZ 62-3	5087.1	56	TZ 243	4453.8	80
TZ 82	5375.2	63	TZ 242	4503.1	60	TZ 243	4469.1	92
TZ 62	4719.4	75	TZ 242	4507.8	81	TZ 243	4474.6	92
TZ 62	4736.5	99	TZ 242	4529.3	108	TZ 24	4473.1	89
TZ 62-1	4894.0	85	TZ 44	4842.8	100	TZ 24	4488.4	56
TZ 62-1	4895.5	127	TZ 44	4845.1	128	TZ 45	6070.4	93
TZ 62-2	4793.5	24	TZ 44	4884.9	85	TZ24	4635.1	87

Table 3 The testing data of the calcite cement samples inside-cave and country rock samples in Tazhong area								
Well wellnumber	Sample type	depth (m)	Trace element ($\times 10^{-6}$)				homogenization temperature ($^{\circ}\text{C}$)	salinity (wt%)
			Sr	Ba	Fe	Mn		
TZ45	The inside-cave calcite cement	6068.5	335	380	620	80	74.5	9.2
TZ 45		6092.3	250	180	620	60	107	2.61
TZ 45		6099.4	231	1200	1060	60	99	4
TZ 45		6102.7	289	223	2710	130	94	4.83
TZ 451		6027.1	230	420	1540	120	100.3	5.75
TZ 26		4276.0	300	81	440	160	125	13.21
TZ 26		4282.8	170	750	340	40	116	6.4
TZ 26		4286.1	190	1400	1440	80	97	7.2
TZ 242		4738.3	220	410	6120	200	103	8.1
TZ 242		4741.7	322	1500	2200	200	85.1	2.55
TZ 242		4750.6	271	1100	880	70	82.5	7.83
TZ 242		4754.8	200	390	550	40	143.5	12.67
TZ 242		4755.9	550	1733	1580	60	127.7	7.63
TZ 242		4756.3	400	2000	1590	70	85.9	1.29
TZ 24		4458.6	300	550	1570	40	126.5	9.2
TZ 24		4460.8	240	540	672	54	64.5	2.16
TZ 62-1		4894.0	200	850	871	66	100	10.1
TZ 62-1		4897.6	200	64	812	86	138.9	10.3
TZ 62-1		4898.4	400	83	320	93	94.6	8.7
TZ 62-1		4952.6	280	69	551	59	73.8	6.5
TZ 62-1		4955.8	251	85	639	112	104	10.7
TZ 62-1		4957.9	100	100	335	104	122	4.93
TZ 62-1		4959.2	130	530	1321	87	115.5	9.65
TZ 62		4714.2	287	3019	1623	51	125.6	11.08
TZ 62		4734.5	350	1988	734	72	126	1.86
TZ 62		4737.2	260	451	376	63	97.5	11.8
TZ 62		4742.4	200	199	890	142	119	12.2
TZ 62		4745.9	180	511	1734	58	72	3.75
TZ 62		4749.3	481	1348	923	65	82	13.11
TZ 45	country rock	6035.4	310	6.6	59	12	/	/
TZ 45		6045.3	395	15	124	8	/	/
TZ 242		4737.1	280	23.9	64	19	/	/
TZ 242		4730.2	100	3.8	93	11	/	/
TZ 62-1		4895.1	190	12.6	89	5	/	/
TZ 62-1		4956.2	167	2.7	91	12	/	/
TZ 62		4743.4	250	7.2	67	15	/	/

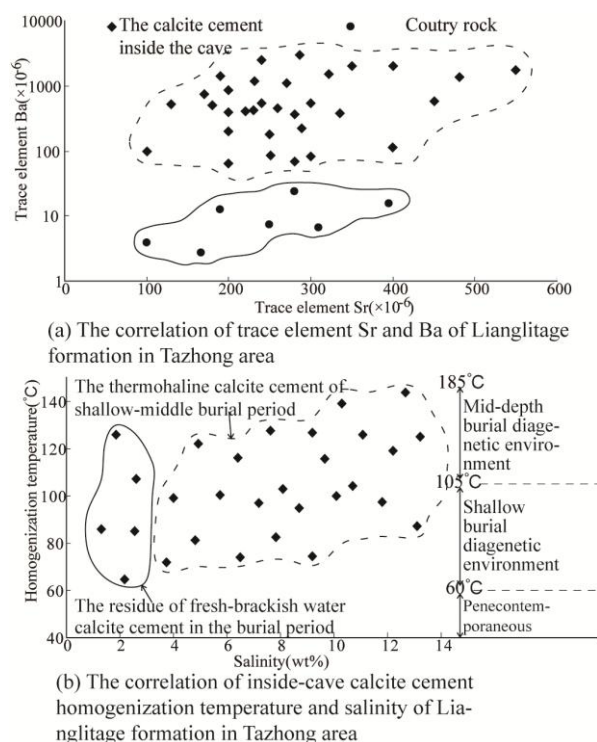


Fig.7 The characteristics of inside-cave calcite cement of Lianglitage formation in Tazhong area

(Fig. 5j-l), which seriously undermine the efficiency of reservoir property. The analysis to the testing data of 29 pieces of inside-cave calcite samples and 7 pieces of country rock samples (Table 3) shows that the content of trace element Sr have no difference between these two categories. However, the content of trace element Ba, Fe, Mn of inside-cave calcite samples are higher than country rock samples, especially Ba content is 10-300 times higher than country rock (Fig. 7a). According to this characteristic we can infer that inside-cave calcite is reformed by burial stage hydrothermal activity. The homogenization temperature and salinity of 31 pieces of inside-cave calcite samples are relatively high and showing positive correlation, with genetic feature of the thermohaline calcite cement in shallow-middle burial period (Fig. 7b). Tazhong area had experienced a long time tectonic movement of the extensional movement at the end of Early Ordovician, the compressional movement at the last period of Ordovician and the strike slip motion at the last period of Silurian²⁷⁻²⁸,

which caused the development of the fault and fracture, thus the formation of thermohaline calcite cement may be affected by deep fluid that produced by Hercynian magmatism.

The three periods of tectonic movement developed in Tazhong area made up a large quantity of faults and fractures, which can be used as the reservoir spaces and seepage channel, and they provided favorable conditions for the above-mentioned deep fluid and meteoric activities, thus be benefit to the capacity and permeation of the reservoir of the reef-bank. Structural movements in the platform margin near Tazhong I fault belt were intense in the Meso-cenozoic burial stage, thus a large number of high angle fractures, diagonal fractures and reticular fractures developed. With the injection of acid water, the fractures and early relic pores-vugs were reformed by multi-stage burial dissolution, which generated dissolved fracture, beadlike dissolved pore and dissolved vug, and the porosity increased about 3%. Therefore, fractures formed in multi-stage tectonic disruptions improved the permeation of reservoir, furthermore, it is benefit to the connection of reservoir and microscopic pore structure. In conclusion, the distribution of the fracture zone has a controlling effect on the distribution of high oil and gas production wells.

Discussion

Stage of tectonic evolution of Tazhong platform decided the growth and spatiotemporal distribution of reef-bank. This pattern enlighten us that the fault-controlled sedimentation still need advanced research. The transformation of different types of fluid in different stages are the key factors of reservoir genesis^{6, 9, 11, 19-20}. Reef-bank reservoir that developed in different types of sedimentary geomorphology is reformed by the different level of syngenetic karstification strength. Therefore, accurate characterization of sedimentary geomorphology

research in Lianglitage Formation is particularly important. Deep fluid plays two roles in carbonate reservoir reconstruction as dissolution and filling^{27, 28}. Analysis of trace element of mud fillings inside caves and the homogenization temperature of the inclusions include the salinity test shows that the reef-bank reservoir may be obviously controlled by the late hydrothermal activity, and it were closely related to magmatic activity in Hercynian stage. Reef-bank is markedly reformed by deep buried fluid in Lianglitage Formation, and this feature is closely related to Hercynian magmatism. Deep fluid reconstructed reservoir is kind of complex reservoir, with various developmental patterns and strong heterogeneity. So the key to understand the reservoir distribution and development pattern is to figure out deep fluid type, fluid migration channel, fracture development, fracture distribution pattern, and the spatiotemporal arrangement relationship between hydrocarbon filling and tectonic activity.

Conclusion

The earliest Ordovician coral stromatoporids reef-building organisms of China is found in the research fills the blank of reef in Late Ordovician. Controlled by high-frequency sea level change and multistage structural evolution of rimmed platform, 4-5 stages reef-bank developed in vertical direction of Lianglitage Formation and moved inside out of platform margin. The reef-bank is clumped and band distribution along platform margin NW-SE. Grain shoal that accompanied with reef(mound) is the most favorable reservoir lithofacies. Dissolution vuggy and caves that formed by karstification in syngenetic-supergene stage are the key factors for the development of reef-bank reservoir. Meanwhile, these pores and caves provide dissolution places for buried deep fluid, and have great potential to form multiple sets of high-quality reef-bank complex reservoir.

Acknowledgement

Authors are grateful to Prof. Zhang Yunfeng and Prof. Qu Haizhou for valuable amendments to this paper, and the Exploration and Development Research Institute of Tarim Oilfield provided strong support to core observation, rock debris observation, thin-slice observation and sampling. Geochemical analysis was done under the help of Southwest Petroleum University Minerals Isotope Laboratory and Electron Microprobe Laboratory

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