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# Genesis of reservoir in deep and reef-bank carbonate rocks of Ordovician in eastern Tazhong area, Tarim Basin, NW China

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Based on the measured physical properties, thin slices, cores and well logging data, this paper researched the characters and genesis of reservoir in the Lianglitage formation of Upper Ordovician in Tazhong area. The average buried depth of the formation was 4868m. There developed four high porosity layers vertically. The average porosity and the thickness of these layers decreased as the depth increases. The reservoir had the features that macro reservoir space layers coincide with the higher matrix porosity layer. The polycyclic thick reef-bank complex which deposited in the suitable deposition environment in Late Ordovician was favorable material basis for developing reservoir, and the reef limb, reef core and bioclast bank were the favorable sedimentary micro-facies. A lot of selective dissolution pores formed by syngenetic karst in the upper part of each reef-bank cycle. The early diagenetic stage karst formed lots of non-selective dissolution pores within 100m from the top, so that the reef-bank complex developed lots of pores with the superimposition, which was the key factor for the quasi-layered reservoir in the upper part of Lianglitage formation. Fractures formed by tectonic disruption communicated the pre-pores during burial stage, and provided migration pathway for multiple fluids. These fluids dissolved the surrounding rock or inhibit the cementation, so that insured the reservoir capacity in the deep buried carbonate rock. The space-time configuration of oil and gas migration and porosity development was preferable. These factors formed the large condensate gas deep reservoir in Lianglitage formation of the Upper Ordovician in Tazhong area.

**Keywords:** Deep reservoir; reef-bank complex; Ordovician; eastern Tazhong area; Tarim basin.

## INTRODUCTION

Oil and gas in deep and ultra deep layers have the character of low permeability and high temperature, even high pressure. For example, the porosity of those layers of folding basins in Western China are less than 10%~12%, and their permeability are less than  $0.5 \times 10^{-3}$ - $1.0 \times 10^{-3} \mu\text{m}^2$ , original formation temperature exceeded 120-150 °C (Pang, 2012). However, over 1000 oil and gas fields

developed in ultra deep layers around the world showed that that original recoverable oil took up seven percentage of the total oil reserve. Gas even took up 25%. There are seventeen found deep carbonate oil and gas fields which had an equivalent oil reservation of 10000 thousand tones. For example, reserve of explored oil in deep formation in Tarim basin was about 79% of the total reserve (Pang, 2012; Ma et al., 2011). Deep reservoir are facing with many difficulties and challenges, such as unclear oil and gas source, unidentified genetic mechanism of reservoir, oil and gas distribution and uncertainty in optimizing exploration target (Sun et al., 2010; Ma et al., 2011;

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Pang, 201) Chinese researchers clarified deep carbonate reservoir in to several kinds according to mainly genesis, karst reservoir, reef-bank reservoir, dolomite reservoir, fracture reservoir, etc (Zheng et al., 2008). This paper gives a general discussion of reservoir in deep and reef-bank carbonate rocks of Ordovician in eastern Tazhong area from genetic aspect.

## GEOLOGIC SETTING

Tazhong No.1 fault belt is located in the north of Tazhong uplift, Tarim basin, with a northwest-southeast trend, which is a complex of early fracture fault belt and late sedimentary fault belt (Wu et al., 2010), and had a tectonic framework of higher east and lower west, and our study area is located in the high structural area in the east (Figure1). When Lianglitage formation deposited in Late Ordovician, the climate was warm, and the sea level rose stably, seawater circulation of Tazhong-Bachu was well, and the salinity was normal. Eastern higher areas with shallow water and strong waves were good for plants' reproduce and produced lots of carbonate, resulting in forming complex sedimentary body of reef and grain bank, which is called reef-bank complex (Wang et al.,2010). Two movements of Late Caledonian which was happened in late Ordovician and Silurian formed the original Tazhong uplift. During this period, the crust rose, so Lianglitage formation was exposed immediately after its deposition, leading an unconformity surface emerge between Lianglitage formation and Sangtamu formation. And Hercynian structural movements made formations of Devonian and Silurian get strong denudation, making the Tazhong uplift totally appear. However, during Indosinian and Himalayan movements, Tazhong uplift fell and rose integrally, and no obvious fractures developed (Zhou et al., 2006).

## RESERVOIR FEATURES

The upper boundary of Lianglitage formation in Upper Ordovician had an average depth of 4868m, maximum depth reached 5603m. Main porosity types of the ultra deep carbonate reservoir were intergranular dissolved pores, intragranular dissolved pores, moldic holes, organic holes and microfissures. Physical property of reservoir was low-porosity and low-permeability. Physical data of 2376 cores from 21 wells showed that the porosity distributed between 0.05% and 12.76%, averaging 1.66%, and the permeability was between  $0.006\mu\text{m}^2$  and  $50\times 10^{-3}\mu\text{m}^2$ , averaging  $0.5\times 10^{-3}\mu\text{m}^2$ , pore throat was fine. However, the matrix porosity of reef-bank carbonatite in Lianglitage formation developed four porous layers, with buried depth of 0~80m, 110m~150m, 160m~185m and 260m~277m away from the upper boundary of Lianglitage

formation, and average porosities were 3.2%, 2.4%, 2.2% and 2.0%, thickness of these layers were 80m, 40m, 25m,17m (Figure2). Marcospace of Lianglitage reservoir in study area are caves (the diameter was bigger than 500mm), pores (the diameter was bigger than 2mm) and fractures (Figure3). These all developed commonly in L2 section to L1 section of Lianglitage formation, 92 m-200m from the upper boundary. Porous layers (Figure3c) observed on the cores were 0.8m~20m thick, and preserved well with a fill percentage of 2%-60%. The diameter of massive caves varied from one meter to dozens of meters, and were half or fully filled by mud, breccia and macrocrystalline calcite (Figure3d), which led mud loss and drill rig unloading during the drilling process, for example, in well TZ62-1 drill rig unloading at the depth of 4959.1m~4959.3m and 4973.2m~4973.76m was  $799.2\text{m}^3$  mud. Multiphase tectonic fractures were identified on the cores, width varied from 0.2mm to 30mm and had different attitude (Figure3e). Commercial oil and gas flow was mainly produced from reef-bank formation in upper Lianglitage formation, coinciding with depth of those sections where caves, holes, fractures and high matrix porosity developed. Therefore, the depth sectors where macro reservoir space and high matrix porosity met were preferable reservoir in L2 section to L1 section, Lianglitage formation.

## RESERVOIR GENESIS

### Sedimentary facies

In Middle-Late Ordovician, Tarim plate was located at  $20^{\circ}\sim 30^{\circ}$  southern latitude, palaeo water temperature was between  $24.22^{\circ}\text{C}$  and  $31.53^{\circ}\text{C}$  (Jia et al.,1995,Wang et al.,2010). In Tazhong area, the climate was warm and wet, lacking of terrestrial clastic, the water was shallow, clear and dynamic, all these conditions were beneficial for carbonate deposition and the growth of reef building organism. The east of Tazhong I fault belt lay in the reef-bank rimmed system of platform edge facies zone (Chen et al., 1999, which can be divided into four subfacies: reef segment, lime mud mound, grain bank and interbank sea, and those four subfacies were divided into several sedimentary microfacies respectively. Lianglitage formation, especially from L3 to L1 section, showed the vertical character of polycyclic combination of reef segment, lime mud mound and grain bank. In each cycle, the lower part developed grain bank subfacies, the middle part developed lime mud mound or reef segment or both of them, and in the upper part it was covered by the grain bank subfacies of the next cycle, and the thickness of each cycle was 100m to 300m. Storage ability of different carbonate sedimentary facies or even different microfacies from the same subfacies was distinguishing.

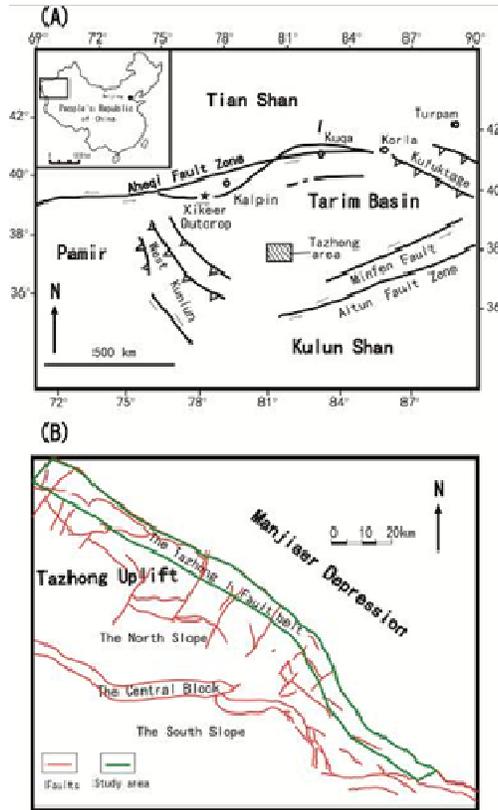


Figure 1. The tectonic location map of research area

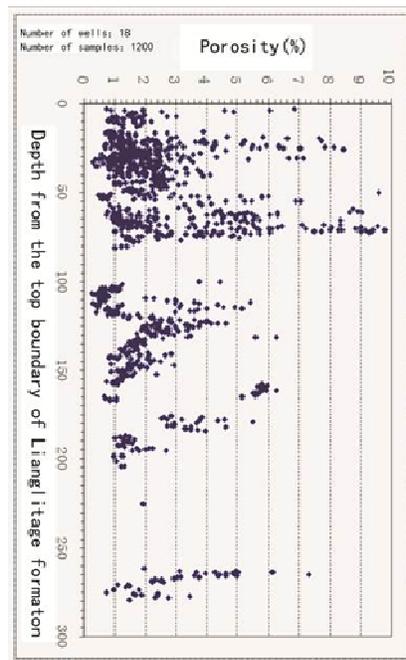
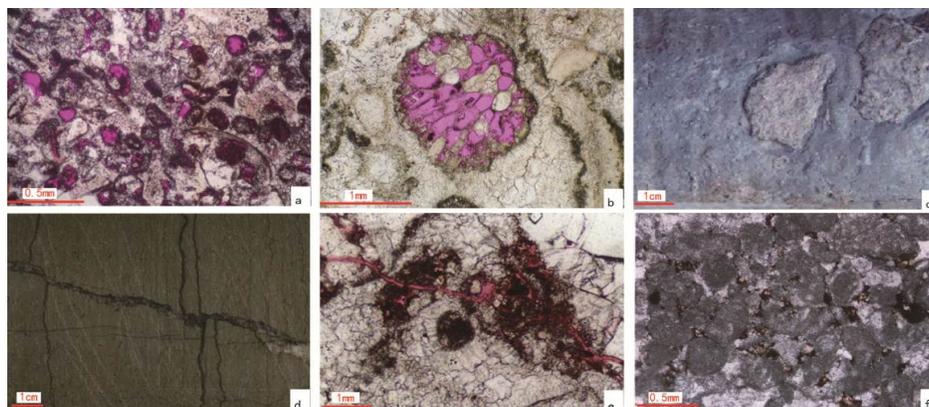


Figure 2 Porosity distribution in different depth in the Lianglitage Formation in Eastern Tazhong area.



**Figure 3.** The reservoir pore space features of Ordovician reef-bank complex, Eastern TaZhong region. a) Intragranular dissolved pores and moldic pores develop in calcsparite biotritus arenaceous limestone of TZ722 in 5014.5m (pores stained red); b) Intragranular pores develop in well TZ54 in 5757.8m, moldic thin slice (-); c) Caves are filled with mud and breccia in cores of well TZ62-2 in 4793.7m; d) Argillaceous ribbons cut by high angle tectonic fractures filled with asphalt and calcite of well TZ35 in 5640.8m; e) Fractures and dissolved vugs along fractures of well TZ161 in 4476m, moldic thin slice (-); f) Intergranular dissolved pores formed after compaction and calcite cementation, mainly filled by asphalt and heavy crude. Well TZ15, 4664.13m, moldic thin slice (-).

Facies of Lianglitage formation in study area was platform edge facies, but different microfacies and different rock types had obvious difference in reservoir physical property (Qiang, 2007, Paul et al., 2010). Physical properties of reef flank, reef core and biotritus microfacies were fine, respective average porosity were 2.45%, 2.15%, 2.12%, lowest porosity occurred in low energy zone, such as mound core and interbank sea. And rock types which had good physical properties were related to biotritus, average porosity was 1.0~1.8%, while porosity of low energy rock was less than 1% (Table 1). It demonstrated that reef limestone and grain rock formed in high environment in the favorable bank edge facies zone were favorable lithological combination. Therefore, thick reef-bank complex in upper Lianglitage formation was essential material foundation for ultra deep reservoir development.

### Superimposed reconstruction of syngenetic karst and early diagenetic karst

#### Superimposed Reconstruction Features

Pores of Ordovician reef-bank complex in Tazhong area were mainly intragranular dissolved pores, moldic pores, intergranular dissolved pores, erratic dissolved pores and small scale caves etc. (Figure 3a-c), meanwhile, pendent-like, crescentic and syntaxial overgrowth cements and fill material like vadose silt also occurred. Large amounts of non-selective dissolutions and fillings emerged after the early diagenetic karst, such as half-full

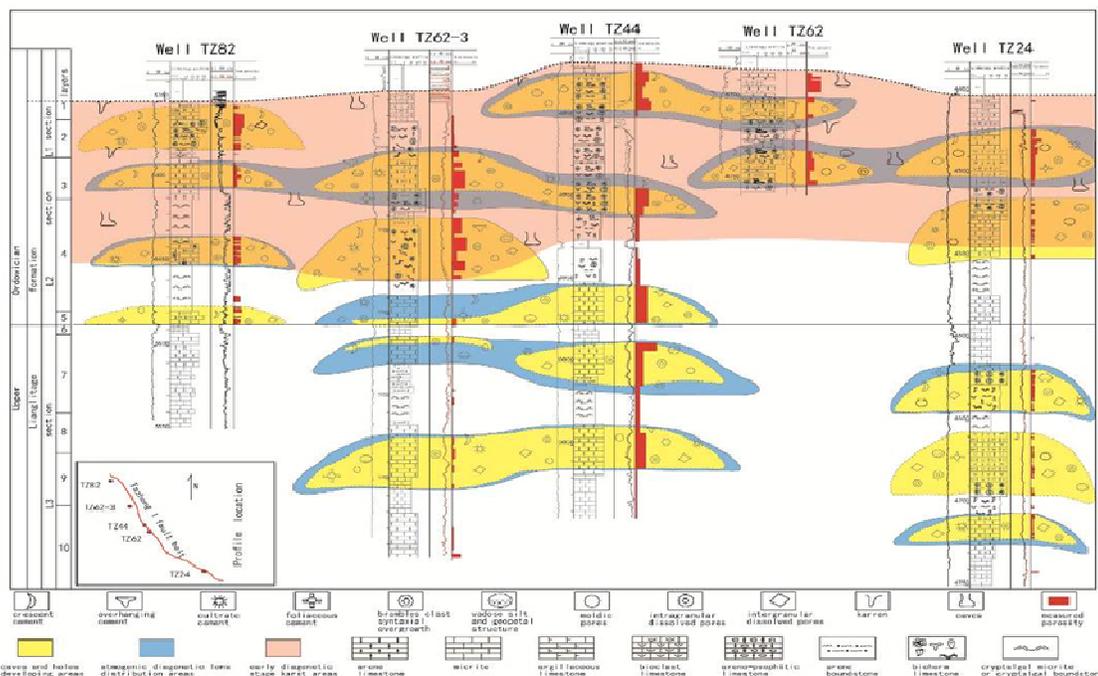
filled dissolved holes with gray green mud and limestone breccia, high angle fractures and karrens (Figure 3d). In addition, the top of Lianglitage formation was denuded to some extent; even in some high areas the first layer of L1 section was totally damaged (Wang et al., 2007). Features of the two behaviors could occur in the same well and even at the same depth, and features of superimposed reconstruction were obvious.

#### Superimposed Reconstruction Process

During penecontemporaneous-contemporaneous period, when the sea level fell down, reef-bank complex at the platform edge got easily exposed to air, and with eluviations of fresh water, aragonite and magnesium calcite and some other unstable minerals dissolved, forming porous layers (without fossil organisms, dissolved evenly and lentiform distribution). Features of syngenetic karst were: (1) it occurred when L3-L1 section deposited, right the time when reef mainly developed; (2) as far as one single bank or reef, available accumulation space were often in the overlying grain rock of the bank or reef because of syngenetic karst; (3) multicyclic depositions of reef-bank complex led to multiphase syngenetic karst vertically in Lianglitage formation. Therefore, multiphase syngenetic karst had some positive functions in reservoir forming, such as improving porosity of reef-bank complex. Lianglitage formation got tectonic compression not long before it was buried, and then it was exposed to air, accepting eluviation, dissolution, and filling because of the early diagenetic karst. The time of early diagenetic karst

**Table 1.** The property distribution list of difference depositional microfacies in Upper Ordovician reef-bank complex, Eastern Tazhong region

Microfacies type	main rock type	porosity(%)				permeability( $10^{-3}\mu\text{m}^2$ )			
		Sample amount	minimum	maximum	average	Sample amount	Minimum	maximum	average
Reef Flank	Algae calcirudite, lime nodule algae calcirudite	170	0.51	10.09	2.45	211	0	25.4	1.1
Reef Platform	Oncolite calcsparite calcirudite and calcsparite calcirudite	337	0.06	9.05	1.73	295	0	448	4.59
Reef core	organic framework , organic calcirudite	53	0.41	5.86	2.15	48	0	145	9.67
Biotrits Bank	Micrite-calcirudite arene limestone	56	0.17	5.09	2.12	38	0.03	9.16	0.76
Mound Platform	Micrite-calcirudite oncolite algae arene limestone, oncolite arene limestone	120	0.24	5.99	1.6	95	0	117	4.86
Arene bank	Micrite-calcirudite oncolite algae arene limestone	326	0.1	3.55	1.16	249	0	492.1	3.61
Mound core	Cryptalgal micrite limestone, cryptalgal bindstone, cryptalgal grumous limestone	311	0.1	7.71	1.02	249	0	116.6	2.03
Interbank sea	Cryptite, clastizoic cryptite, shaly limestone Argilliferous limestone etc.	151	0.16	4.1	0.86	103	0	47.6	1.04



**Figure 4.** The characteristic pattern of superimposed dissolution of syngenetic karst and early diagenetic stage near-surface karst of Ordovician reef-bank complex, Eastern TaZhong region

was not long, and it did not damage or reconstruct all the features of syngenetic karst, so features of the two functions could be identified in the same well, and we suppose that the exposure surface was formed in the period of transition from nearshore exposure surface to continental exposure surface (Esteban et al., 1983). Tazhong area was partly exposed to air, only in the high areas, especially the thick reef-bank complex sedimentary areas. Early diagenetic karst made some further eluviation and dissolution to forward uplift reef-bank complex, which was beneficial for further development of pore spaces.

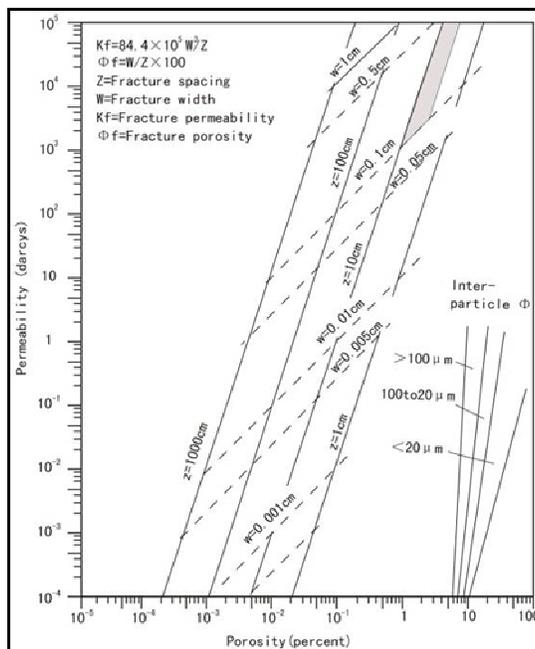
### Effect of Superimposed Reconstruction

Sea level changed frequently when reef-bank complex deposited in Tazhong area, Late Ordovician. Syngenetic karst formed multiphase selective dissolved pore space, each porous layer was 10~30m thick, coinciding well with single reef-bank cycle vertically, and the total thickness of porous layers was great. After deposition, sediments were exposed to air without going through the process of middle-late diagenesis, then new non-selective karrens, fractures and caves occurred in the reef-bank complex in Lianglitage formation because of vadose and dissolution from early diagenetic karst, and it happened in the layers

which were less than 100m from the erosion surface, mainly in L1 section and L2 section (Figure 4). Although some selective dissolved pores was damaged by the diagenetic karst, the non-selective dissolved pores had improved porosity obviously. Thus, the two karst processes was continuous geologically, and had some significant meanings in increasing pore space and improving permeability, the unconformity surface formed during the two processes was important in oil and gas transition and accumulation.

### Tectonic disruption

There was no obvious relation between porosity and permeability in carbonate reservoir, but porosity and permeability increased significantly once the fracture got wider and the interval of fracture decreased (Lucia et al., 1983, 2007). Fractures were commonly distributed in Lianglitage formation of Tazhong area because of multiphase tectonic activities, and three phase fractures and fractures expanded by corrosion could be identified on the cores. The width of fractures were between 0.2 and 30mm, mainly distributed from 1 to 2mm, and fracture density were between 5.37 to 11.32 cracks per meter, averaging 11.05 cracks per meter. Parameter of fractures in Figure 5 showed that fractures had a positive



**Figure 5.** The relationship of porosity to permeability of different fracture parameters (Lucia, 1983), the ashy part represent fracture feature of study area.

contribution in improving porosity and permeability of reef-bank reservoir in study area. Influenced by varieties of fluid media, fractures turned into dissolved fractures, moniliform dissolved holes and caves, and then formed a new reservoir and seepage combination together with the remaining caves and holes formed before, even with cementation of some minerals like calcite (Figure3e-f), connectedness and permeability of reservoir had been improved generally. Figure 5

#### Water-rock interaction in burial stage

Positive features of underwater-rock interaction in improving porosity are listed below: 1) chemical reactions occurred between acid formation water and surrounding rock. 2) Fluid transition hindered cementation. Carbonate formation of Tazhong area experienced at least three phase buried karst in the long burial time. Fluids transition coincided well with tectonic movements both in time and space. Fluids of different source flew through those fractures and pore spaces and then reacted with the surrounding rocks, forming embayed pores, pores distributed along fractures and dark asphalt or some microcrystalline cements in the boundary between pores and surrounding rocks (Figure3e-h). We even found some crude oil in the pores of some cores, for example, in TZ45 well eight wide fractures(0.3-10mm wide) was on the

cores in the depth of 6047.80m-6072m, and was filled by macro crystalline calcite, fluorite and anhydrite, tawny crude oil seeped out of the remaining pores during coring process.

#### CONCLUSIONS

Reservoir in deep and reef-bank carbonate rocks of Ordovician in eastern Tazhong area was deep, and macro reservoir space layers coincided with the higher matrix porosity layers. Average reservoir depth is 4868m, and four porous layers developed vertically. Layers in the sections less than 80m from the upper boundary of Lianglitage formation have the best physical properties and a good thickness. The average porosity and the thickness of these layers decrease as the depth increases. Macro caves, holes and fractures mainly developed in L2 to L1 section.

Multicyclic and thick reef-bank complex in middle-upper Lianglitage formation of Upper Ordovician are important for the development of ultra deep reservoir. Reef flank, reef core and bioclast bank are the best microfacies. Superimposed reconstruction of the two karst processes in different periods was a key factor in ultra deep reservoir developing. Large amounts of selective dissolved pores formed by syngenetic karst were formed

in the top of each reef-bank cycle because of syngenetic karst, while non-selective pores formed by early diagenetic karst reconstructed reef-bank complex within 100m from the upper boundary of Lianglitage formation. Thus, horizontally stable quasi-layered reservoir developed at the top of Lianglitage formation.

The fact that multiphase fractures coincided well with multiphase dissolution during burial stage is an important guarantee for reservoir development. Fractures formed by tectonic disruptions reconnected pores formed before. Varieties of fluids transited along these fractures, then dissolved surrounding rocks or hindered cementation in pores, guaranteed the permeability of deep buried carbonate rocks. With all the factors, the first ultra deep condensate gas reservoir in reef-bank complex of Ordovician was formed.

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