Tectonic evolution of Tarim basin in Cambrian–Ordovician and its implication for reservoir development, NW China

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In order to find the impact of regional tectonic evolution of Tarim basin on the inside distribution of sedimentary facies and reservoir development, this paper, based on the research of plate-tectonic evolution of Tarim basin, conducts an in-depth analysis on the basin's inside sedimentary response to the Eopaleozoic regional geodynamic reversion from extension to convergence around Tarim plate, and concludes that the regional geodynamic environment of surrounding areas closely contributes to the formation and evolution of paleo-uplifts, differentiation of sedimentary facies in platform, distribution of high-energy reef and bank facies belts, conversion of sedimentary base level from fall to rise, obvious change of lithology from dolomite to limestone, and formation of several unconformity surfaces in Ordovician system in the basin. A series of sedimentary responses in the basin are controlled by regional dynamic setting, which not only controls the distribution of reservoirs in reef and bank facies but also restricts the development and distribution of karst reservoirs controlled by the unconformity surfaces. This offers the macro geological evidences for us to further analyze and evaluate the distribution of favorable reservoirs.

1. Introduction

Tarim basin is located in northwest China (figure 1) and it is one of the largest hydrocarbon-bearing intracontinental basins in the world. It is adjacent to Tianshan Fold Belt in the north, to Kunlun Fold Belt in the southwest, and to Altyn Uplift in the southeast. Tarim is a cratonic basin with Archean and Paleo- to Meso-Proterozoic crystalline basement. Sedimentary cover is composed of Neo-Proterozoic, Paleozoic, Mesozoic and Cenozoic. The Neo-Proterozoic is lithologically characterized with the moraine-breccia, sanderstone, mudstone and dolostone, and the Cambrian–Ordovician dominantly consisting of carbonates in the western platform facies area and sandstone with mudstone in the eastern basin facies area (table 1).

There have been many researches and discussions about the tectonic evolution of Tianshan, Kunlun and Altyn orogens around the Tarim plate (Wang 1983; Hopson *et al.* 1985; Wang *et al.* 1990, 1995, 1999; Xiao *et al.* 1990, 1991; Guo *et al.* 1993; Hao and Liu 1993; Ma *et al.* 1993; Pan *et al.* 1994; Deng 1995; Ding *et al.* 1996; Liu *et al.* 1996, 1999, 2002, 2004; Jiang *et al.* 1999; Solomovich and Trifonov 2002; Yang *et al.* 2002, 2005, 2006; Zhao *et al.* 2003; Han *et al.* 2004; Zhou *et al.* 2004; Gao *et al.* 2006; Qin *et al.* 2006; Zhu *et al.* 2006), as well as about the structural and depositional character in the Tarim basin (Guo *et al.* 1995; Jia *et al.* 1992, 2004; Kang and Kang 1994; Tang 1994, 1997a, b; Jia 1997; Zhao 1997; Tang *et al.* 2004; Lin *et al.* 2011). But the relationship between regional tectonic activities and the geological responses within

Keywords. Basin dynamics; sedimentary response; reservoir; Cambrian–Ordovician period; Tarim basin.

Figure 1. Sketch map of tectonic setting around Tarim basin. 1. Suture of plates; 2. Deep fault; 3. Thrust fault belt of foreland; 4. Reserve fault; 5. Strike slip fault; 6. Uplift. ① Nikolaev line, ② Kangxiwar fault belt, ③ Altyr fault belt.

Tarim basin, especially the impact of regional geodynamic setting on depositional evolution and reservoir development inside the basin leaves unclear.

With the cracking of Rodinia Supercontinent, the regions around Tarim basin began extension since Neoproterozoic, and the evolution of Tarim basin in the Neoproterozoic and Palaeozoic went through two complete extension–convergence cycles, namely Neoproterozoic (Nanhua period)–Devonian period cycle and Carboniferous–Permian period cycle (Jia *et al.* 1992, 2004; Kang and Kang 1994; Tang 1994, 1997a, b; Guo *et al.* 1995; Jia 1997; Zhao 1997; Tang *et al.* 2004). The first cycle went through the cracking to form the continental rift around Tarim Plate since Later Neoproterozoic (Nanhua period), the extension to form passive continental margin in the Cambrian period, subduction and collision during the Ordovician–Silurian–Devonian period. Accordingly, the deposition inside Tarim basin shows specific responses. For different geodynamic settings of surrounding regions, there are different characteristics of depositional lithologies and lithofacies, sea-level change, distribution and migration of sedimentary facies, etc., in the Tarim basin. Under the condition of regional extensional dynamic setting around Tarim Plate, there formed the Manjia'er rift and a series of small half-graben faults in the plate and the passive continental margin along the plate margin. The convergent dynamic setting of surrounding regions caused the formation of paleo-uplift and differentiation of palaeogeomorphology, and controlled the distribution of sedimentary facies in the basin. As can be seen from the above, the regional geodynamic setting around Tarim

basin exerted significant control over its petroleum geological conditions; especially, the geodynamic reversion of surrounding regions from extension to convergence in the geotectonic cycle which play a key role in the fundamental change of sedimentation in the plate. Therefore, having a correct knowledge of sedimentary response to the regional geodynamic reversion around Tarim basin has theoretical and practical significance to instruct the oil and gas exploration activities in this area.

2. Tectonic setting of Tarim basin in Cambrian–Ordovician

The Tarim Plate belongs to a continental one with crystalline basement of Pre-Neoproterozoic, which is situated between Tianshan and Kunlun orogenic zones. The Tarim Plate includes the stable area of Tarim basin and the surrounding multi-stage marginal activity belts (Jia 1997; Jia *et al.* 1992, 2004). It is confined by suture zone of South Tianshan (namely the Nikolaev Line, also called South Tianshan tectonic belt) as north boundary, Kangxiwar suture zone (Kunlun orogenic belt) as the southwest boundary and Altyr fault zone (Altyr orogenic belt) as the southeast boundary, respectively (figure 1) (Huang *et al.* 1990; Xiao *et al.* 1990, 1991; Zhang 1994; Tang *et al.* 1995; He *et al.* 2005).

2.1 North boundary

The Tarim Plate is adjacent to the Kazakhstan Plate on the north. The fault at north margin of South Tianshan (namely the famous Nikolaev Line) serves as the dividing line between Tarim

Table 1. *Stratigraphy and lithology of Cambrian and Ordovician in Tarim basin.*

Chronostratigraphy				Lithostratigraphy and lithology	
Era	System	Series	Stage	Carbonate platform facies area in the western Tarim basin	Basin facies area in the eastern Tarim basin
Paleozoic	Ordovician	Upper	Hirnantian		
			Katian	Shantamuo Fm: black mudstone	Yinpinshan Fm: turbidite sandstone and mudstone
			Sandbian	Lianglitage Fm: micrite, wackstone, packstone, grainstone, boundstone and reef framestone	
		Middle	Darriwilian	Yijianfan Fm: micrite, wackstone, packstone and grainstone	Zhatupuo Fm: sandstone, silty mudstone and mudstone Querqueke Fm: turbidite sandstone and mudstone
			Dapingian		
			Floian	Yingshan Fm: thin-to-middle bedded dolomite in the lower portion while interbedded micrite, bioclastic limestone, and silicalite in the upper portion	Heituwa Fm: black shale, silty mudstone and radiolarian silicalite
		Lower	Tremadocian	Penglaiba Fm: middle to thick-bedded dolomite	Baiyungan Fm: thin-bedded micrite and black shale
	Cambrian	Furongian	Stage 10	Xiaqiulitage Fm: thick-bedded dolomite	
			Stage 9		
			Paibian		
		Series 3	Guzhangian		Tershakitage Fm: black shale
			Drumian		
			Stage 5	Awatage Fm: red dolomite, limestone, muddy dolomite, mudstone and siltstone	Muohershan Fm: micrite, muddy limestone and mudstone
	Terreneuvian	Series 2	Stage 4		
			Stage 3	Shayilike Fm: dolomite and muddy dolomite Wusonggeer Fm: middle to thin-bedded dolomite	Chuanxinshan Fm: thick bedded biolithite limestone Xidashan Fm: dolomite, limestone and mudstone
			Stage 2	Xiaoerbulak Fm: thick-bedded dolomite	Xishanbulak Fm: black shale, silicalite, silicious mudstone and phosphorite
		Fortunian			
			Fortunian	Yuertusi Fm: black shale, silicalite, phosphorite and dolomite	
Neo-Proterozoic		Ediacaran			Hangerqiaoke Fm: moraine-breccia and mudstone Shuiquan Fm: dolostone interbedded silty mudstone
					Yuekengou Fm: sandstone, silty mudstone
		Cryogenian			Tereiaken Fm: sandstone, mudstone and moraine-breccia Aletongou Fm: dolostone, limestone, sandstone, mudstone and moraine-breccia
					Beiyixi Fm: basalt, trachyte, andesite and felstone
Mid-Proter				Crystalline basement	

Plate and Kazakhstan Plate (figure 1). During the Later Paleozoic Era, the subduction of South Tianshan Ocean made the Tarim Plate collided with Kazakhstan Plate and finally connected with each other, forming the complicated tectonic belt in the South Tianshan area. Now, the ophiolite is distributed along the Nikolaev Line (SMS in figure 2). Since the Palaeozoic South Tianshan Ocean is the north ocean crust of Tarim Plate, namely one part of the Tarim Plate, the north boundary of palaeozoic Tarim Plate should coincide with the fault at north margin of South Tianshan (Nikolaev Line).

2.2 Southwest boundary

The southwest margin of Tarim Plate also went through the complicated evolution, including the northward subduction of Early Paleozoic Kudi Ocean, the formation of Early Paleozoic Kunlun island arc and Kudi suture (figure 3), close of the Later Paleozoic Paleo-Tethys Ocean along the Kangxiwar mélangé belt (figure 3). After that, the

south regions experienced the assembly of Qiangtang terrain at the end of Triassic Period and Lasa terrain at the end of Jurassic Period as well as the Indian–Eurasian continent collision since the Oligocene Epoch, but they all fall within the domain of Neo-tethys structure (figure 1). Therefore, the Kangxiwar suture zone can be taken as the southwest boundary of Palaeozoic Tarim Plate (figure 3).

2.3 Southeast boundary

On the southeast of Tarim Plate, there runs the world-famous Altyn Fault Belt (figure 1), which belongs to a large sinistral strike-slip fault of Mesozoic and Cenozoic Era, especially the latter. Its large-scale strike slip in the Mesozoic and Cenozoic Era totally changes the previous geological structure features. According to the relevant researches and the discovery of ultra-high pressure metamorphic rocks in the Altyn region in recent years, the southeast margin of Early Paleozoic Tarim experienced the complicated divergence and convergence and tectonic evolution processes

Figure 2. Distribution of the ophiolites in the Tianshan mountains (modified from Gao *et al.* 1998). 1. Paleozoic strata; 2. Pre-Cambrian basement; 3. Paleozoic granites and island volcanic; 4. Ophiolites; 5. Klippe of ophiolites; 6. High pressure metamorphic rocks; 7. Thrust fault; 8. Mesozoic and Cenozoic strata; NMS: North suture of Middle Tianshan mountains; SMS: South suture of Middle Tianshan mountains (Nikolaev Line); NTF: North marginal fault of Tarim basin. ① Gangou ophiolite; ② Mishigou ophiolite; ③ Wushitegou ophiolite; ④ Luweigou ophiolite; ⑤ Bayingou ophiolite; ⑥ Changawuzhi ophiolite; ⑦ Guluogou ophiolite; ⑧ Yishugou ophiolite; ⑨ Tonghuashan ophiolite; ⑩ Liuhangshan ophiolite; ⑪ Mishibulake ophiolite; ⑫ Kulehu ophiolite; ⑬ The ophiolite at 965 km of Du-Ku Highway; ⑭ Sherekeyayilake ophiolite; ⑮ Keketiekedaban ophiolite; ⑯ Dalubayi ophiolite and ⑰ Heiyinshan ophiolite.

Figure 3. Tectonic sketch map of west Kunlun area. 1. Forland thrust belt; 2. Basic volcanic rock; 3. Flysch Formation; 4. Granite; 5. Melange accumulation; 6. Intermediate and acid rock; 7. Suture zone; 8. Ophiolite. ① Kudi suture zone; ② Ta-Ka suture zone; ③ Hongshanhu suture zone; Ku: Kudi; M: Mazha; Ka: Kangxiwa; Mu: Muji; Ta: Tashikuergan.

(Zhang 1994; Liu *et al.* 2002). The Altyn Fault Belt can be taken as the southeast boundary of the Tarim Plate.

3. Determination of regional geodynamic reversion

Tarim basin is clamped between the Later Paleozoic southern Tianshan Orogen at the north and the Early Paleozoic Kunlun orogen at the southwest. Because the Altyn Fault Belt at the southeast of the basin is a strike-slip fault of Mesozoic and Cenozoic Era, the geodynamic setting of Tarim basin in Paleozoic Era is controlled by the evolution of the two orogens at the north and southwest.

3.1 Evolution of southern Tianshan Ocean in Early Paleozoic

Cambrian is a period with rapid cracking of supercontinent, and the separation of Siberia paleocontinent comes into being the paleo-Asia Ocean, in which the southern Tianshan Ocean is the southern branch (Xiao *et al.* 1990, 1991). Ordovician is the key period for the evolution of paleo-Asia

Ocean. Ophiolites distributing in the southern Tianshan give us evidence to reveal the formation of southern Tianshan Ocean.

Former researches show that there are two zones of ophiolites in the southern Tianshan orogen (figure 2), in which the northern one distributes along the line of Gangou, Mishigou, Wushitegou, Bayingou and Luweigou (①-②-③-⑤-④ in figure 2), and the southern in the area of Heiyinshan, Kulehu, Du-Ku Highway and Yushugou (⑥-⑦ in figure 2) (Wang *et al.* 1990, 1999; Gao *et al.* 1998, 2006). The ages of 452–640 Ma of the ophiolites at the core area of Yushugou from the southern ophiolite zone (⑧ in figure 2) (Zhou *et al.* 2004) and of 590–600 Ma of the ophiolites at the Dalubayi from the northern ophiolite zone (⑩ in figure 2) (Yang *et al.* 2005) indicate that the southern Tianshan area was developed into ocean in the Later Precambrian. The ages of the ophiolites from the two zones cover from 452–640 Ma (⑧ Yushugou), 590–600 Ma (⑩ Dalubayi), 439 Ma (⑥ Changawuzi), 420–430 Ma (⑦ Heiyinshan), 425 Ma (⑫ Kulehu), 358 Ma (⑦ Guluogou) to 333 Ma (⑬ Du-Ku Highway) (Hao and Liu 1993; Wang *et al.* 1995;

Liu *et al.* 1996; Zhou *et al.* 2004; Yang *et al.* 2005; Gao *et al.* 2006; Long *et al.* 2006), suggest the continuous development of southern Tianshan Ocean in the Paleozoic Era.

Intermediate-acidic rocks corresponding to subduction of plate in the southern Tianshan provide us with the information of time and process on the subduction of southern Tianshan Ocean crust. The ages of such granide corresponding to subduction as biotite granites, monzogranite, granodiorite and so on in the middle area of southern Tianshan, cover from 436 to 355 Ma (Hopson *et al.* 1985; Yang *et al.* 2006; Zhu *et al.* 2006), suggest a continuous subduction in the Later Paleozoic Era. The large difference of ages from these granides occurring in the middle area of southern Tianshan indicates the difference of subduction process from west to east. The dating researches for high pressure metamorphites, granides and volcanics from the western section of southern Tianshan Orogen indicate that the collision process between Tarim Plate and Yili block began at 345 Ma (Early Carboniferous) and ended approximately at 300 Ma (the end of Carboniferous) (Gao *et al.* 2006). The age of 436 Ma of the zircon from dioritic granite at Nalatishan in the middle section of southern Tianshan Orogen suggests that the subduction of southern Tianshan ocean crust down to under the Yili-Middle Tianshan block began at least in the Early Silurian (Zhu *et al.* 2006), which is also supported by the occurrence of the Upper Silurian island-type volcanics at the Nalatishan (Gao *et al.* 1998). It was reported that the collision at the Hongliuhe area in the eastern section of southern Tianshan Orogen might take place 412 Ma ago (Guo *et al.* 1993). The U–Pb ages of zircons from the granites in Bayinbuluke, Yeyungou and Kumishi areas forming an Early Paleozoic orogenic process are (490–380 Ma) (Han *et al.* 2004), suggest that the subduction of southern Tianshan ocean crust in the eastern section of southern Tianshan Orogen might begin at 490 Ma (Early Ordovician). It can be seen that the orogenesis of southern Tianshan Orogen is a process of scissor-type collision earlier in the east and later in the west. The earliest subduction in the eastern section of southern Tianshan Orogen might take place at the Early Ordovician.

Some other evidence, such as the age of 313 Ma from the youngest island-type volcanics (Zhu *et al.* 2006), Ar–Ar ages of 306–250 Ma from the volcanics and shallow intrusive rocks forming in the later collision period (Zhao *et al.* 2003), the ages of 280–266 Ma from the moyites and 275–260 Ma from the alkalic rocks brought in the post-collision period (Jiang *et al.* 1999; Solomovich and Trifonov 2002; Liu *et al.* 2004), indicates that collision and orogenesis of the southern Tianshan Orogen ended

at the end of Carboniferous, and then it went through the period of post-collision evolution.

3.2 Evolution of western Kunlun Ocean in Early Paleozoic

The ophiolites in the western Kunlun area distribute mainly along the zone of Muji, Tashikuergan, Kudi and Kangxiwa (figure 3). There are many ophiolite bodies such as Kudi ophiolite, Kegang ophiolite, Wuyitage ophiolite, Muji ophiolite and so on, in which Kudi ophiolite is the most typical.

Kudi ophiolite is composed of ultramafites and gabbro at the lower portion, the basic volcanics and flysch formation at the upper portion, which is the best researched geological body in this area. The characteristics of petrology and geochemistry of Kudi ophiolite indicate that it is the residuals of Kunlun Ocean crust (Wang 1983; Deng 1995). There are different ages reported from the Kudi ophiolite. The Rb–Sr age of amphibole from the amphibolite vein in the ultramafic intrusive rocks shows 860.5 Ma (Wang 1983). The model age of 600–900 Ma is got from the pillow basalt (Pan *et al.* 1994). Ding *et al.* (1996) reported the 651 Ma of the bulk Sm–Nd isochron age from the gabbro. These ages from the ophiolite suggest the occurrence of Kudi Ocean (north-western Kunlun Ocean) in the Later Precambrian.

There develop great amount of Early Paleozoic acidic-intermediate intrusive rocks and volcanics at the southern side of the suture zone of Muji-Kudi, including diorite and granodiorite bodies at the northern Kudi, granite bodies at Buzhiwangou, northern Kudi, northern Kanxiwa, Wuyitage, Wanbaogou and so on, which distributes discontinuously in this belt covering more than 600 km long. Former researches from petrology and geochemistry indicate that these acidic-intermediate rocks generated in the arc tectonic settings (Ma *et al.* 1993) with the subduction of Kudi Ocean southward. The isotopic ages of these rocks are mostly between 449 and 494 Ma (Jia 1997), suggesting the subduction began at the Early Ordovician. It can be inferred that the Kudi Ocean may close at the end of Ordovician from the great deal of supply of terrigenous clasts from western Kunlun into Tarim basin in the Silurian.

3.3 Evolution of Altyn Ocean in Early Paleozoic

Because of the large scale of strike-slip along the Altyn Fault Belt in Mesozoic and Cenozoic Era, the evolution of Altyn Ocean in the Early Paleozoic is not as clear as those of southern Tianshan Ocean and western Kunlun Ocean. It is recently reported that there is a destructive ophiolite zone

composed of basic–ultrabasic rocks with the feature of oceanic crust (Yang *et al.* 2002; Qin *et al.* 2006). The Sm–Nd age of 508 ± 41 Ma from the ophiolite illustrates the existence of Altyn Ocean in the Early Paleozoic (Liu *et al.* 1999, 2002). The close of Altyn Ocean is suggested at the end of Early Paleozoic (Qin *et al.* 2006).

Summarizing the tectonic evolution of southern Tianshan and western Kunlun orogens, it can be seen that the extension around the Tarim Plate began at the Later Precambrian and generated southern Tianshan Ocean at the north and western Kunlun Ocean at the southwest, also the Altyn Ocean at the southeast, and the subduction of the southern Tianshan Ocean in the eastern section and that of the western Kunlun Ocean started at the Early Ordovician. From this, we can conclude that the geodynamic reversion from extension to convergence around the Tarim Plate began at the Early Ordovician, which results in a series of depositional response inside the basin.

4. Sedimentary response in Tarim basin to Ordovician region geodynamic reversion

With the regional geodynamic reversion from extension to convergence in the surrounding area of Tarim Plate at the Early Ordovician Epoch, the sedimentation in the Tarim basin shows

specific responses. In fact, these sedimentary characteristics are also the evidences to support the surrounding regional geodynamic reversion.

4.1 Fast filling of Manjia'er Aulacogen

The Manjia'er Aulacogen began opening to form the rift in the Neoproterozoic with the deposition of typical coarse clastic rocks. There continuously developed the bathyal facies composed of black mudstone, siliceous mudstone and muddy limestone from Cambrian through the lower portion of the Lower Ordovician with thin thickness of approximately 300 m (figure 4). The well TD1 was bored in the Manjia'er Aulacogen. It shows that the lower portion of the Lower Ordovician consists of black shales with thickness of 50 m, and the upper portion of the Lower Ordovician is composed of the rhythm layers of grey litharenite, silty mudstone and shale, with thickness of 270 m. The sandstone mainly consists of tuff, rhyolite and felsite debris coming from volcanic island arc (Zhou *et al.* 1991), suggesting the existence of active continental margin with island arc in the late stage of Early Ordovician Epoch. Then the extremely thick turbidite system characterized by sandstones interbedded with argillaceous rocks in rhythm manner occurred in the Middle and Upper Ordovician (figure 5). In the Manjia'er region, the

Figure 4. Distribution of paleo-uplifts at the end of Early Ordovician Epoch in Tarim basin. S–S' shows the location of the seismic section of figure 6.

As can be seen from the above materials, the Kuluktagh and Manjia'er regions have been converted from the cracked continental margin basin into convergent basin since the late stage of Early Ordovician Epoch, which may be related to the subduction of east section of south Tianshan Ocean. In the Middle–Late Ordovician Epoch, the Manjia'er Aulacogen was rapidly filled with the clastic rocks, terminating the evolution history of Manjia'er Aulacogen (figure 5).

During the Cambrian–Ordovician period, several paleo-uplifts developed in the Tarim basin with different causes of formation (figure 5). The cracking and extension in the southern Tianshan and western Kunlun regions from Neoproterozoic to

4.3 Differentiation of sedimentary facies in the platform

Except for the Manjia'er depression, the Cambrian–Ordovician System in the Tarim basin is mainly composed of carbonate platform. In the Cambrian Period and Early Ordovician Epoch, the platform-marginal facies depositing in high-energy environment were distributed along the west margin of Manjia'er depression, and the depositional facies in the west carbonate platform showed no obvious differentiation (figure 7a). Since the sedimentary period of Yingshan Formation in the late Early Ordovician Epoch, the differentiation of facies in carbonate platform became gradually

Figure 6. Opposite direction onlap reflection of Tazhong Uplift in the Lower Ordovician. The seismic section location is shown in figure 5. T80, T74 and so on are the seismic reflection surfaces. T100, T90, T80 and T70 are the bottom surfaces of Neo-Proterozoic, Cambrian, Ordovician and Silurian, respectively. T74 is the bottom surface of Upper Ordovician. T72 is the top surface of Shantamuo Fm. T75 is an unconformity in Yingshan Fm. T81 is the bottom surface of Upper Cambrian. The red areas represent the reef build-ups in Upper Ordovician.

Figure 7. Patterns of carbonate platform in Tarim basin. (a) Cambrian Period–Early Ordovician Epoch; (b) Middle and Late Ordovician Epoch.

obvious; firstly, a lot of carbonate shoals were formed inside the platform during the sedimentary period of Yingshan Formation. The long axis directions of these shoals are approximately perpendicular to the principal compressive stress resulting from the convergence of southern Tianshan and west Kunlun oceans in the later Early Ordovician Epoch, representing the discrepancy of depositional topography (figure 8). After that, the Awati–Manjia'er depression took shape inside the carbonate platform in the Middle and Late Ordovician Epoch, dividing the platform into three parts distributed in the east–west direction (figure 7b); the high-energy facies along the platform margin also changed its distribution from the south–north

direction (along the Manjia'er) to the nearly east–west direction (along the uplift in platform) (figure 7). Such differentiation and migration of inner-platform facies are closely related to the formation of paleo-uplift in the platform and the change of palaeogeomorphology resulted from the geodynamic evolution around the Tarim basin.

4.4 Formation of unconformity surfaces

With the reversion of geodynamic setting around Tarim basin and the formation of uplift in platform, there developed many different orders of unconformity surfaces on the paleo-uplifts in the Ordovician System during the periods of sea level

Figure 8. Distribution of shoals in the Tazhong and Southwest uplift area of Tarim basin in Yinshan Formation of the Lower Ordovician. 1. Marginal bank of carbonate platform; 2. Marginal facies zone of carbonate platform with high energy; 3. Shoal inside the carbonate platform; 4. Facies zone with high energy inside the carbonate platform; 5. Carbonate platform; 6. Slope facies; 7. Shelf and basin facies; 8. Well; 9. Basin margin; 10. Fault; 11. Erosional margin.

fall. According to the latest research results, the unconformity surfaces between the Penglaiba Formation and Yingshan Formation in the Lower Ordovician were discovered at the Keping and Yingshan outcrop sections and their characteristics were discussed (Deng *et al.* 2008). There exist the regional unconformity surfaces between Lower, Middle and Upper Ordovician Series and between Lianglitage Formation and Sangtam Formation in the Upper Ordovician (Deng *et al.* 2008). These unconformity surfaces mainly distributed in the Paleo-uplift regions. There are obvious depositional hiatuses and onlap of above strata on these unconformity surfaces and top-lap with cutting off of strata under these surfaces in the Tabei, Tazhong and southwest paleo-uplift regions (figure 9), suggesting the control of paleo-uplifts and palaeogeomorphology on the development and distribution of the unconformity surfaces.

4.5 Change of the lithofacies and base level

There occurs an obvious transition in lithofacies and base level at the beginning of the Ordovician in Tarim basin (figure 10). The Cambrian is composed of dolomite, then the Lower Ordovician is turned into the dolomite interbedded with limestone and the Middle-Upper Ordovician is completely changed into limestone. Accordingly, the

base level changes from a gradual fall upward in the Cambrian to a rise in the Ordovician, forming a turnaround at the beginning of the Ordovician.

In conclusion, this series of sedimentary responses inside the basin to the reversion of regional geodynamic setting not only controlled the spatial distribution and migration of facies belt of carbonate reservoirs, but also created conditions for the development of karstification.

5. Geological significance of regional dynamic reversion to reservoir

The regional geodynamic reversion from extension to convergence around the Ordovician Tarim basin resulted in the differentiation of uplift-depression pattern in the basin and a series of sedimentary responses. Such changes exert significant control over the development of carbonate reservoir in the basin.

During the extension period of Cambrian and the start of Early Ordovician Epoch, there developed the Manjia'er depression in the eastern Tarim and the carbonate platform in the western basin. There was a slope between the western carbonate platform and the eastern Manjia'er depression (figure 11). Accordingly, the bank facies with high energy are mainly distributed on the east margin of platform along the west of Manjia'er (figures 12,

Figure 9. The seismic profile showing the T_7^4 unconformity surfaces across the Tazhong Uplift. The T_7^4 reflection surface was levelled in the profile so that the onlap structure on the surface and the top lap beneath the surface can be seen more clearly.

Figure 10. Change of base level and lithology of Cambrian–Ordovician in Tarim basin. 1. Limestone; 2. Calcarenite; 3. Stromatolite limestone; 4. Muddy limestone; 5. Nodular limestone; 6. Dolomite; 7. Stromatolite dolomite; 8. Muddy dolomite; 9. Nodular dolomite; 10. dolarenite; 11. Mudstone; 12. Calcilitite; 13. Siltstone; 14. Sandy mudstone; 15. Phosphorite. The sequence stratigraphy and change of base level are from Yu *et al.* (2001).

Figure 11. Seismic profile showing the migration of banks in Cambrian and the Lower Ordovician. The profile location is shown as P-P' in figure 12.

Figure 12. Distribution of bank facies with high energy on the east margin of platform in the period of Cambrian and Early Ordovician Epoch. 1. Bank facies of platform margin in Early Cambrian; 2. Bank facies of platform margin in Middle Cambrian; 3. Bank facies of platform margin in Late Cambrian; 4. Bank facies of platform margin in Early Ordovician; 5. Basin margin; 6. Fault. P-P' is the location of a seismic profile shown in figure 11.

15a) and characterized by the gentle-slope and epicontinental-sea carbonate platform (figure 11).

The regional geodynamic reversion from extension to convergence around the Tarim basin in the Early Ordovician Epoch caused the formation and evolution of paleo-uplifts in the basin. The formation of paleo-uplifts and differentiation of palaeogeomorphology, together with the sea-level change, have a joint control over the development

of carbonate platform and spatial distribution of favourable reservoir facies belts.

The development of carbonate shoals of Yijianfang Formation in the central region of Tarim basin indicates that the differentiation of palaeogeomorphology corresponding to the regional dynamic reversion in the Early Ordovician resulted in the deposition of shoals on the relative shallow areas inside the carbonate platform (figure 8).

The marginal slope of paleo-uplift and the sea-level change together restricted the characteristics of development, migration and distribution of the reef and bank facies belts in the platform margin (figure 15c, d). And the marginal high-energy facies belts of the carbonate platform experienced obvious migration with the change of tectonic geomorphology and sea level. During the Middle–Late Ordovician Epoch, with large-scale rise of sea level, the carbonate platform marginal facies belts migrated to the palaeogeomorphic highland controlled by the paleo-uplifts, resulting in the occurrence of platform marginal reef and bank facies belts around the Tazhong and Tabei Paleo-uplifts which is characterized by the rimmed carbonate platform (figures 7b, 13 and 15e, f).

The formation and evolution of paleo-uplift geomorphology not only restricted the distribution of sedimentary facies favourable for reservoir, but also controlled the strength and stages of large-scale karstification under the unconformity surfaces. Furthermore, the syngenetic paleo-kasts are also developed on the geomorphologic highlands on the paleo-uplifts. The research shows that the paleo-uplift highland and paleo-slope zone controlled by paleo-uplifts serve as the favourable areas for large-scale karst development under

unconformity surfaces (figure 15b); and in such areas, the superposition of multi-stage karstification can greatly improve the reservoir quality, and the paleo-uplift highlands of Tabei, Tazhong and southwest uplifts, all controlled the development of karst reservoirs in and around them.

At the top highland of Tabei Uplift, Ordovician was eroded out and the Cambrian carbonate was covered by carboniferous clastics. The Yijianfang Formation of Middle Ordovician was kept along the slope area of the Tabei Uplift, which was also covered by carboniferous clastics. In the Tazhong Uplift, the Yinshan Formation of the Lower Ordovician was covered by Lianglitage Formation of the Upper Ordovician, where the Middle Ordovician is lacunal. In the Southwest Uplift, the Yinshan Formation of the Lower Ordovician was covered by carboniferous clastics. Thus it can be seen that there are hiatuses with different stages after the Middle or Early Ordovician in these paleo-uplift areas. Based on the stages and duration of these hiatuses, it can be concluded that the karstification on the Middle or Lower Ordovician under the unconformity is the strongest in the paleo-uplift areas, accordingly, the best karst reservoirs in the Middle and Lower Ordovician are developed in the paleo-uplift highland and paleo-slope zone.

Figure 13. Carbonate reef and bank reservoir distribution in the Middle and Upper Ordovician. 1. The reef and bank reservoir of Yijianfang Formation in the Middle Ordovician discovered by drilling wells; 2. The reef and bank reservoir of Lianglitage Formation in the Upper Ordovician discovered by drilling wells; 3. Distribution of favourable reef and bank reservoir in the Middle and Upper Ordovician; 4. Carbonate platform facies; 5. Shelf and turbidite facies; 6. Fault; 7. Erosion margin; 8. Basin margin; 9. Drilling well.

Figure 14. The karst reservoir distribution in the Middle and Lower Ordovician. 1. The best first grade of karst reservoir distribution of Yijianfang Formation in the Tabei Uplift and of Yinshan Formation in the Tazhong and Southwest uplifts; 2. The second grade of karst reservoir distribution of Yijianfang Formation in the Tabei Uplift and of Yinshan Formation in the Tazhong and Southwest uplifts; 3. The third grade of karst reservoir distribution of Yinshan Formation in the Tazhong and Southwest uplifts; 4. Carbonate platform facies; 5. Shelf and basin facies; 6. Fault; 7. Erosion margin; 8. Basin margin; 9. Drilling well.

Figure 15. The reservoir characteristics of Ordovician carbonate rocks. (a) Well Gc2, O1p, 3412.7 m, crystalline dolomite, all of the fractures are filled by calcite; (b) Well Z13, O1y, 5845.1 m, dolomitic limestone with small solution pores; (c, d) Yijianfan outcrop, O2yj, baffling reef with solution pores; (e) Well Tz44, O3l, 4879.02 m, boundstone with solution pores; (f) Well Tz44, O3l, 4882 m (X50, orthogonal), calcarenite with intragranular pores, hydrocarbon filling. The well location is shown in figures 12 and 13.

6. Conclusions

The tectonic dynamic settings around Tarim basin experienced the reversion from extension to convergence in the Early Ordovician Epoch. Accordingly, a series of sedimentary responses were formed in the Tarim basin, including:

- (1) fast filling of Manjia'er Aulacogen;
- (2) formation of paleo-uplifts;
- (3) obvious differentiation of the paleogeomorphic framework and the change of distribution of platform marginal high energy facies belts;
- (4) the conversion of sedimentary base level, which was accompanied by the change of lithology;
- (5) development of many unconformity surfaces in the Ordovician system.

The above series of sedimentary responses not only controlled the spatial distribution and migration of favourable carbonate reservoir facies belts, but also created conditions for the development of karstification. The carbonate reef and bank reservoirs are favourably distributed along the east margin of carbonate platform facing the Manjia'er depression to the east in the Cambrian and the Lower Ordovician with the extensional dynamic setting, and distributed around the paleo-uplifts in the Middle and Late Ordovician with the convergent dynamic setting. The favourable karst reservoirs in the Middle and Lower Ordovician are developed in the paleo-uplift highland and paleo-slope zone.

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