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Tectonic types and evolution of Ordovician proto-type basins in the Tarim region

HE DengFa[1†], ZHOU XinYuan[2], ZHANG ChaoJun[3] & YANG XiaoFa[1]

[1] Energy Resources School, China University of Geosciences, Beijing 100083;
[2] PetroChina Tarim Oilfield Company, Korla 841000, China;
[3] Research Institute of Petroleum Exploration and Development, PetroChina, Beijing 100083, China

The Ordovician system is an important target for exploration in the Tarim Basin. Restoration of the Ordovician tectono-depositional environment is a key basis for the study of the structural development history in Tarim block and the prediction of the favorable Ordovician reservoir belts (zones). Based on the surrounding tectonic settings, the litho-facies and sedimentary fill, the palaeo-geography, palaeo-climate and palaeo-ecology, and the structural deformation and magmatic eruptions, in this paper we combine the sedimentary fill in the basin with the development of the surrounding orogenic belts and re-build the proto-type basins of the different Ordovician periods. During the Ordovician period, the Tarim region was characterized by the composite of the interior cratonic depression with the peripheral cratonic depression. The interior cratonic depression in the central and western parts is mainly the depositional area of the platform facies while the peripheral cratonic depression in the eastern part is mainly the zone of deepwater basin facies, with the slope acting as the transition belt between them. During the Late Ordovician period, the closure of the Northern Kunlun Ocean and destruction of the trench- arc-basin system in the Altyn Tagh region put the southern part of the Tarim block under compression and uplifting and turned the central and western parts of the carbonate platform into the mixed depositional continental shelf. The eastern region of the basin had the over-compensated flysch sedimentation with huge thickness, marking the drastic turn of the basin nature. The basin tectonic framework turned to the south-north differentiation of the Silurian period from the east-west differentiation of the Ordovician period.

Ordovician period, proto-type basin, composite basin, basin evolution, Tarim block

The Tarim Basin is a large-scale superimposed and composite basin developed on the pre-Sinian continental crust basement[1−10]. The main body of the basin is superimposed by the Sinian-Early Permian sequence of the marine facies and the Late Permian-Quaternary sequence of continental facies[3,7−10].

The Ordovician system is the main sequence in the Tarim Basin, where the thickness is between 2000 and 6000 m. The Ordovician system is mainly composed of shallow-water carbonate rocks in the most area of the basin. Therefore, the Ordovician system is one of the desirable regions for the study of the changes in global sea level, the comparison of sea level fluctuations[11,12], the study of the properties, development and migration of the Tarim block[13], the study of the sequence stratigraphy, and the comparison of the cratonic basin genesis and development sequences[13−19]. Meanwhile, the different periods of the Ordovician epoch in the Tarim region are characterized by the obvious east-west differentiation and the south-north differentiation as well as the drastic variation in the tectonic framework. That is why the Ordovician period is also one of the key

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†Corresponding author (email: hedengfa282@263.net)

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geological periods for an in-depth analysis of splitting of the continental blocks, interactions of the surrounding blocks and conversion of the basin-mountain relationships.

The Ordovician system is the dominant exploration target series in the Tarim Basin. A series of Ordovician oil and gas fields have been so far discovered, such as Lunnan-Tahe oil and gas field[20–22], Yingmaili oil field (group)[23], Hetianhe gas field[24], and Tazhong 1 oil and gas field (group)[25]. These oil and gas fields are mainly distributed in North Tarim, Central Tarim and Bachu uplifts and their slopes. The high-energy facies belts (such as reef and beach facies) and the late-stage karst formed the high-quality reservoirs[21,22,25]. However, no systematic and in-depth studies have been currently carried out on the types, periods, distribution and genesis mechanism of the platform that restricted the development of the high-energy sedimentary facies belt[14,26]. The depressions developed in the platform, the slopes on the margin of the platform, the types of organic rock facies belts in the basin, the palaeo-ecological environment, and the sedimentary rock facies[27] are also short of the systematic analysis from the angle of the depositional environment and palaeo-geographic development[28, 29].

The analysis of the tectonic setting, the litho-facies and palaeo-geography, the depositional fill process and the superimposing and overlapping development in the Ordovician Tarim region is of theoretical importance and exploration value to understanding of formation and development of the Tarim Basin and prediction of the favorable Ordovician reservoir rock belts and play fairways.

Currently, more than 200 wells drilled in the Tarim Basin encountered the Ordovician system, distributed within the area of the basin other than Kuqa region. The exploration wells, such as Wells He 4, Fang 1, Kang 2, Tacan 1, Tazhong 1, Tazhong 162, Kunan 1 and Tadong 1, unveiled the Ordovician system. A large quantity of high-quality seismic data has been acquired from the seismic exploration of Lower Paleozoic carbonate rocks. Meanwhile, a series of new breakthroughs have been made in the surface geological investigation in the areas of Altyn Tagh, West Kunlun Mountain and South Tianshan Mountain[30]. Based on these new data and knowledge, the paper uses the proto-type basin analysis method to restore the tectono-depositional environment of the Tarim region in the different Ordovician geological periods and discusses development of the tectonic framework[7, 31, 32].

1 Surrounding tectonic setting and evolution

The Rodinia, a super-continent of the Late Proterozoic period, started splitting from the Sinian period. The periphery of the Tarim block appeared in the form of oceanic crust in the Cambrian period. The Sinian system, unconformably covered on the pre-Sinian crystalline basement, became the first set of overlying rocks in the Tarim block. In the Sinian period, the differentiation of southern and northern uplifts and depressions came into being on Tarim block. It developed into the east-west differentiation in the Cambrian-Ordovician period[29, 33,34]. The whole basin was covered with the Cambrian deposits. The structural pattern was basically turned into "high in the west and low in the east" from the "south-north differentiation" with the sea between the southern land and the northern land in the Sinian period.

The Ordovician period is the key stage for development of Palaeo-Asian Ocean. The following is the main events taking place in the surroundings of the Tarim block.

1.1 Northern branch of Palaeo-Asian Ocean subducted and closed

The northern branch of Palaeo-Asian Ocean closed in the early stage of the Middle Ordovician period. Altai continental block collided with Siberia continent, leading to orogenesis accompanied with syn-orogenic granites. As a result, the Altai folded belt of the Early Paleozoic is connected to the southwestern margin of Siberia Plate as its overgrown continental crust.

The northern Tianshan oceanic basin subducted towards central Tianshan terrane along the Aibi Lake to the southern margin of Turpan-Hami block. The zone from Tangbale to Mishigou and Kangguer Tagh was an Ordovician island arc with Boluokenu and Halkeshan regions on the southern side located in the extended retro-arc basin. Destruction of this oceanic basin ended at the end of the Ordovician period. The Lower Silurian clastic rocks containing graptolite overlaid unconformably above the melange of the Ordovician "Kekenaike" group[35, 36].

1.2 Southern branch of Palaeo-Asian Ocean —— South Tianshan Ocean —— shaped

There were two ophiolite belts in the South Tianshan Mountain[37–39]. The northern belt was from the western Chang'awuzi, Guluogou and Laobaluntai to Ma'anqiao, north of Mishengou. The southern belt was from Heiying Mountain and the northern slope of Hela Mountain to Yushugou[40], south of Kumishi and also extended westward to Kuokeshale, northwest of Aheqi City. Gabbro in the Chang'awuzi ophiolite on the northern margin of South Tianshan Mountain was (439.4±26.9)Ma by ^{40}Ar-^{39}Ar dating[41]. This age indicates the period of South Tianshan oceanic basin expansion and existence of the oceanic basin in the Ordovician period. The age of zircon in the Dalubayi ophiolite of the northern belt is 590—600 Ma[42], likely to indicate the earlier time of the South Tianshan oceanic basin. The ophiolite of the southern belt is Late Silurian-Early Devonian[35], indicating much earlier development of the oceanic basin. Extending eastward to Yushugou and Kumishi region, the ophiolite structurally invaded into the Middle Devonian strata. Of the ophiolite structure, the ophiolite in Yushugou experienced metamorphism of Devonian granulite facies[40]. South Tianshan Mountain of the Ordovician period was mainly the flysch mixed with carbonate rocks. The deposition of the slope and neritic to bathyal facies under the passive continental margin developed along the northern margin of Tarim block.

1.3 Northern Kunlun Ocean subducted and closed

Ophiolite of West Kunlun is distributed mainly along the line of Wuyi Tagh, Kudi, Aqikekule Lake and Xiangride[9,37,38]. Early Paleozoic neutral and acidic intrusion rock and volcanic rock in large quantities developed south of this suture zone[38,43–45], such as northern Kudi diorite, granodiorite, northern Kudi granites, northern Kangxiwa granites, Wuyi Tagh granites, Wanbaogou granites, intermittently distributed for more than 600 km. The isotope ages of these rocks are mainly of 449—494 Ma, belonging to the Ordovician period. The neutral and acidic intrusion rock was formed in the island arc[9]. Namely, North Kunlun Ocean subducted and dwindled southward along the above-mentioned suture zone, leading to the Early Paleozoic island arc magmatic rock zone located on the northern margin of central Kunlun terrane.

This subduction peaked during the Middle Ordovician period, causing volcanic process and intrusion on a large scale. Meanwhile, it also caused extensive development of volcanic debris and pyroclastic sedimentation in the Middle Ordovician strata within the basin. For example, Well Tazhong 31 encountered a set of Middle and Upper Ordovician diabase. The intrusion rock of this period is very clear on the seismic profile. The center of intrusion rock is in the shape of funnel, obliquely penetrating the Middle and Upper Ordovician and invading outwardly along most regional formations. Usually, the intruded bodies do not penetrate the Silurian, indicating the main invasion took place in the Late Ordovician period[34].

North Kunlun Ocean was close to closure at the end of the Ordovician period.

1.4 Trench-arc-basin system on northern margin of Altyn Tagh formed and destructed

Xu et al.[13] connected the northern zone of Altyn Tagh with the northern Qilian zone and the southern zone of Altyn Tagh with the southern Qilian zone, including their correlations of volcanic island arc belts, ophiolite belts and (super-) high pressure metamorphic rock belts. Although there are some controversial on the regional tectonic framework, the tectonic setting study of granite and volcanic rock indicated that the northern margin of Altyn Tagh was likely to have development of a complete set of trench-arc-basin system in the Early Paleozoic period. The northern side was the Middle and Late Ordovician Yutiannan-Ruoqiang retro-arc basin while the neutral and acidic intrusion rock zone and the volcanic rock of the two-peak style developed on the southern side along Altyn Tagh Fault. It was formed in the island arc background. Trench developed on the southern side. In recent years, the study was made of the super-high pressure garnet buchnerite and super-high pressure garnet-containing granite gneiss in the area of Altyn Tagh's Yinggelishayi. The study demonstrated that the super-high pressure rock was formed thanks to deep subduction of the continental crust[46–48], further proving the existence of this trench. The southern and northern facies belts differentiated along Bashikaogong fault in the retro-arc basin. Sulamuning area on the southern side was mainly the sedimentation of platform and marginal shallow water facies while Lapeiquan area on the northern side was a series of huge-thickness acidic and basic volcanic rock and clastic rock formation interbedded with limestone of deep basin facies. It contained Biachiopoda of the Caradoc period of Middle Ordovician, called Yapuqiashayi Formation. This retro-arc basin disappeared in Late Ordovician.

2 Litho-facies and depositional environment

The Ordovician sedimentary development was apparently controlled by the basin structural evolution in this period. The different faulted block activities in the Tarim Basin increased between the end of Late Cambrian and the beginning of Early Ordovician. The elevating faulted block became an underwater uplift while the rapidly subsiding area became bathyal to abyssal basin, accumulated with huge-thickness terrigenous detrital turbidite. The Ordovician period was a period for large-scale transgression and the whole Tarim block was nearly submerged. The transgression reached the peak in the Middle and Late Ordovician periods. The Ordovician period experienced a whole cycle of transgression and regression. The cycle was composed of two sub-cycles[13], transgression from the early stage of Early Ordovician to the middle stage of Middle Ordovician and regression in the late stage of Middle Ordovician as well as transgression in the early stage of Late Ordovician and regression in the middle to late stage of Late Ordovician. Broad and extensive carbonate platform developed in the central and western parts of the basin. The carbonate platform evolved into mixed continental shelf in the late stage of Late Ordovician, marking the turn of the basin nature[19, 49].

2.1 Early Ordovician

In Early Ordovician, the Tarim Basin basically inherited the palaeo-geographic pattern from Late Cambrian. The scope of platform expanded apparently. The carbonate platform extended eastward about 40 km into the basin-facies area, marking the peak period of platform development. The strata were thick in the west and thin in the east with the differences in sedimentary thickness being dozens of times.

The East Tarim area was an under-compensated deepwater basin in Early Ordovician (Figure 1). The sedimentation was very thin, mainly fine particles. Well Tadong 1 unveils a set of grey micrite to silty limestone and gray and gray-black knotty micrite to silty limestone mixed with gray-black calcareous mudstone in the upper part and dark-gray and gray-black crystalline limestone in the lower part. The drilled thickness was 147 m. Organism was mainly deepwater plankton. There was development of graptolite assemblages and thin shell Brachiopoda assemblage[50]. The depth of sea water was higher than 3500 m. The area of Well Kunan 1 and Well Mancan 1 to Qiemo was an east-tilting horseshoe slope with the sea water depth ranging from 50 m to 200 m.

There was development of calcareous detrital and calcareous turbidite sedimentation on the platform of the frontal slope facies, which was intercalated inside static water knotty mudstone. The depositional type referred to gentle slope. The organism included both benthic and plankton as well as both originally buried and allochthonous organism transported by the gravity current from the platform. There was development of Agnostus-thin shell Brachiopoda assemblage.

The extensive area west of the slope was carbonate platform environment with the water depth less than 20 m[14, 27]. The huge-thickness carbonates was deposited in Bachu and Central Tarim areas during this period (the thickness might reach 2200 m). It was characterized by restricted to semi-restricted platform in the early stage of Early Ordovician. The deposits were mainly dolomite and limy dolomite. There was development of semi-restricted to open platform in the late stage of Early Ordovician. The deposits were mainly dolomite limestone and limestone. Horizontally, it was unfolded in the area of Well Qu1, Well He4, Well Manxi 2, Well Manxi 1 and Well Tazhong4, where there was a narrow and arc-shaped restricted platform. Take Central Tarim area for instance, the upper Qiulitagh Formation($O_{1\text{-}2}s$) was the restricted platform of thick gray and shallow gray micrite limestone, bright crystalline micrite calcaremite, chert cemented limestone, dolomite limestone and thick shallow-gray micrite and silty dolomite. The drilled thickness reached 1906.5 m at Well Tazhong1. In addition, there was a restricted platform in Yingmaili area, which covered a small area and was nearly in the east-west direction. Huge-thickness carbonates of open platform facies developed in the most parts of the region other than this area.

2.2 Middle Ordovician

Based on the study of palaeomagnetism and the analysis of carbon and oxygen isotopes, the Middle and Late Ordovician Tarim Block was located in the tropical to subtropical zone at south palaeo-latitude 20°—30°[11,51]. The palaeo-geography changed significantly owing to the rise of sea level in Middle Ordovician. East Tarim

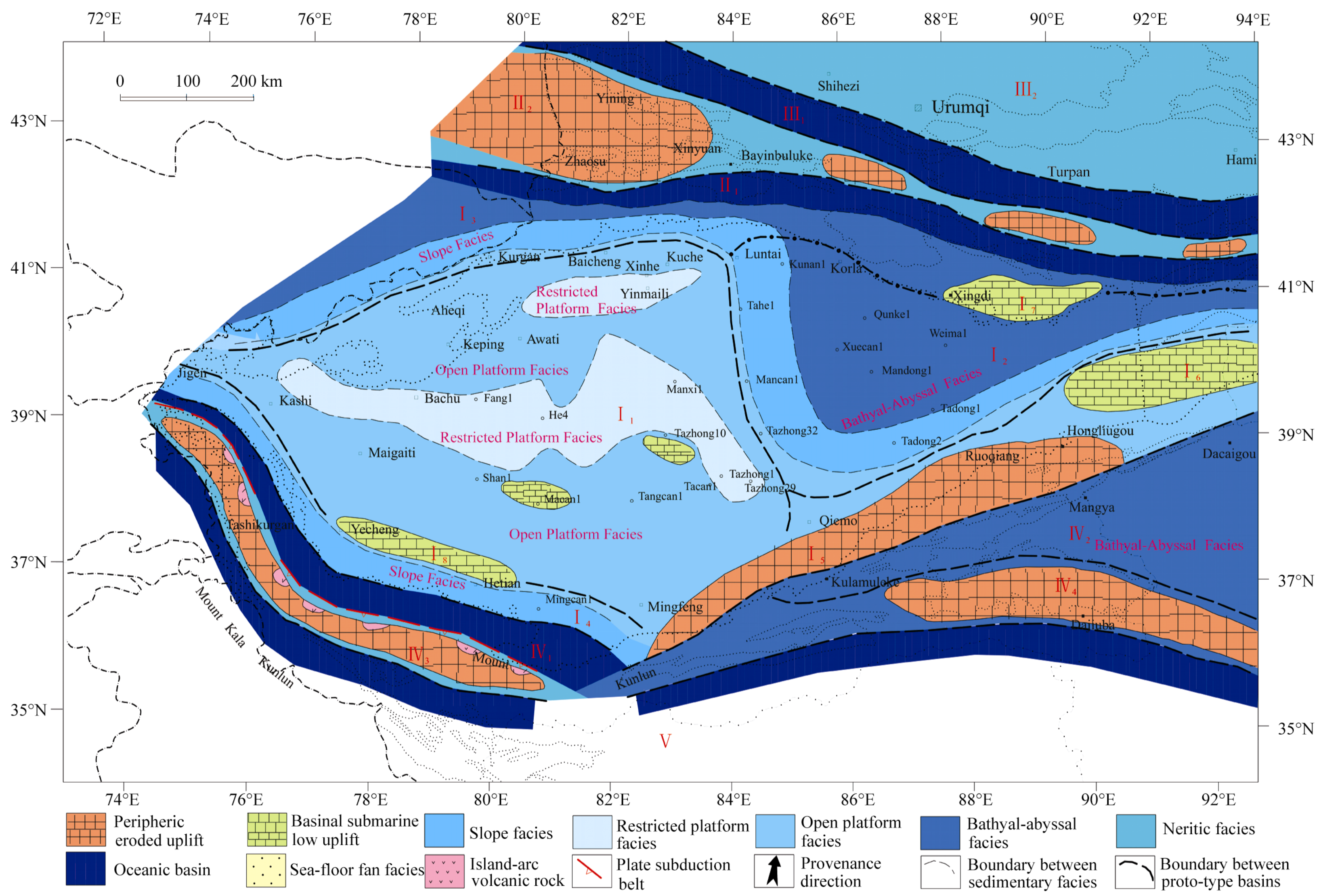

Figure 1 Early Ordovician tectono-depositional environment of Tarim Basin and adjacent areas. I_1, West Tarim interior cratonic depression; I_2, East Tarim marginal depression; I_3, North Tarim passive continental margin basin; I_4, Southwest Tarim passive continental margin basin; I_5, Altyn Tagh uplift; I_6, Luobuzhuang uplift; I_7, Kuokesu uplift; I_8, Hetian low uplift; II_1, South Tianshan oceanic basin; II_2, Central Tianshan uplift; III_1, North Tianshan oceanic basin; III_2, Junggar-Turpan-Hami block; IV_1, North Kunlun oceanic basin; IV_2, Qimantage trough; IV_3, West Kunlun uplift; IV_2, East Kunlun uplift; V, Ancient Kunlun ocean.

area is a basin facies region with the sea water depth becoming higher and the abyssal deposition more obvious. Sea water invaded into Altyn Tagh area.

Manjiaer depression was accumulated with high-thickness terrigenous clastic turbidite of submarine fan sub-facies and muddy shale of basin plain sub-facies. The submarine fan sourced from the northeastern and southeastern directions as well as Central Tarim low uplift. The thickness of the fan body exceeded 2000 m. The east-tilting slope area in Early Ordovician migrated westward approximately 100 km (Figure 2) till the Middle Ordovician period, but the width decreased. Meanwhile, the trend of the slope zone saw an obvious change in the southern part of the basin. The slope zone run across Central Tarim uplift and extended towards the Well Tangcan1-Well Mincan1 area. Tangguzibasi depression subsided significantly for the first time, leading to the bathyal to abyssal environment. The slope was mainly composed of static-water muddy limestone and knotty limestone mixed with calcareous detrital and turbidite deposites. Well Tazhong 29 unveiled the top interval of Middle Ordovician characterized by slope facies while Well Kunan1 unveiled the base interval of Middle Ordovician. The composite progradational configuration features of this slope zone are clearly shown on the seismic reflection profiles.

The southern part of the area surrounded by the U-shaped slope zone (Figure 2) was mainly the platform deposits, but the thickness was less than 1000 m. The deposits were mainly micrite limestone, micrite calcarenite and arene micrite limestone. The northern part was mixed continental shelf with huge-thickness deposits of siltstone and mudstone occasionally intercalated with carbonates. The thickness was as high as 2000 m. The Well Lunnan14-Well Yangwu2-Well Tazhong31 area on the eastern margin of the platform had development of rimmed-like platform beach sedimentation in the late stage (Guniutan stage) of Middle Ordovician. The deposits were mainly bright granular (arene, bioclastic and oolite) limestone.

Central Tarim uplift started to develop along the zone of Wells He 4, Fang 1, Kang 1, Shan 1, Tangbei 2, Tazhong 60, Tazhong 54 and Tazhong 49 in Middle Ordovician. It began to rise and experienced denudation in the late period of Middle Ordovician. The elevation and denudation lasted till the early stage of Late Ordovician, but lack of the intervals of the Dawan period to the Miaopo period. Central Tarim Fault I started to be active from Middle Ordovician and formed the growth fault-propagation fold belt, which had the controlling influence upon its sedimentation of its upper side and lower side. There was biohermal and beach facies on the upper side of the fault, making the important oil and gas reservoir in Central Tarim region.

There was the slope facies on the western margin of the basin, west of the Bachu-Awati-Baicheng zone.

2.3 Late Ordovician

Significant changes took place in the palaeo-geographic pattern of the Tarim Basin in Late Ordovician owing to increase of structural activities and rapid rise of the sea level.

The compensated to over-compensated deposition formed in East Tarim region in correspondence with the large amplitude of subsidence, where the huge-thickness terrigenous clastic turbidite of basin submarine fan and muddy shale of bathyal to abyssal facies were accumulated. The Querqueke Formation ($O_{2\text{-}3}q$) was extensively distributed in East Tarim area (as encountered at wells Tazhong28, 29, 31, 32, 33 and Tadong1). The formation was the rhythmic bedding mainly composed of gray green, yellow, purple red, black or gray sandstone, siltstone, shale and arene limestone. The drilled depth is 1599 m. It was the flysch or typical turbidite sedimentation, producing graptolite, Chitinozoan, conodont, trilobite, Brachiopoda and coral.

A westward convex horseshoe slope zone was close to the western side of the basin-facies area. However, this slope zone already migrated westward a long distance (Figure 3). The main body was located in the area of Wells Lunnan 14, Yangwu 2, Tazhong 49, Tazhong 25, and Tangcan1. With a large width, it was a sedimentary gentle slope, which was a platform-basin transitional zone in the early stage (the sedimentary stage of Tumuxiuke Formation and Lianglitage Formation) of Late Ordovician. It was composed of calcareous clastic and static water knotty limestone and cryotalgalaminate micrite clotted limestone. The palaeontological fossil included plankton Agnostus in addition to abundant benthic organism. The conodont fossil assemblage was the mixture of North Atlantic type and North American Continent type. This slope changed into the mixed deepwater continental shelf in the late stage (the depositional period of Sangtamu Formation) of Late Ordovician. The deposits were mudstone and sandstone intercalated with cryotalgalaminate-sponge limestone and

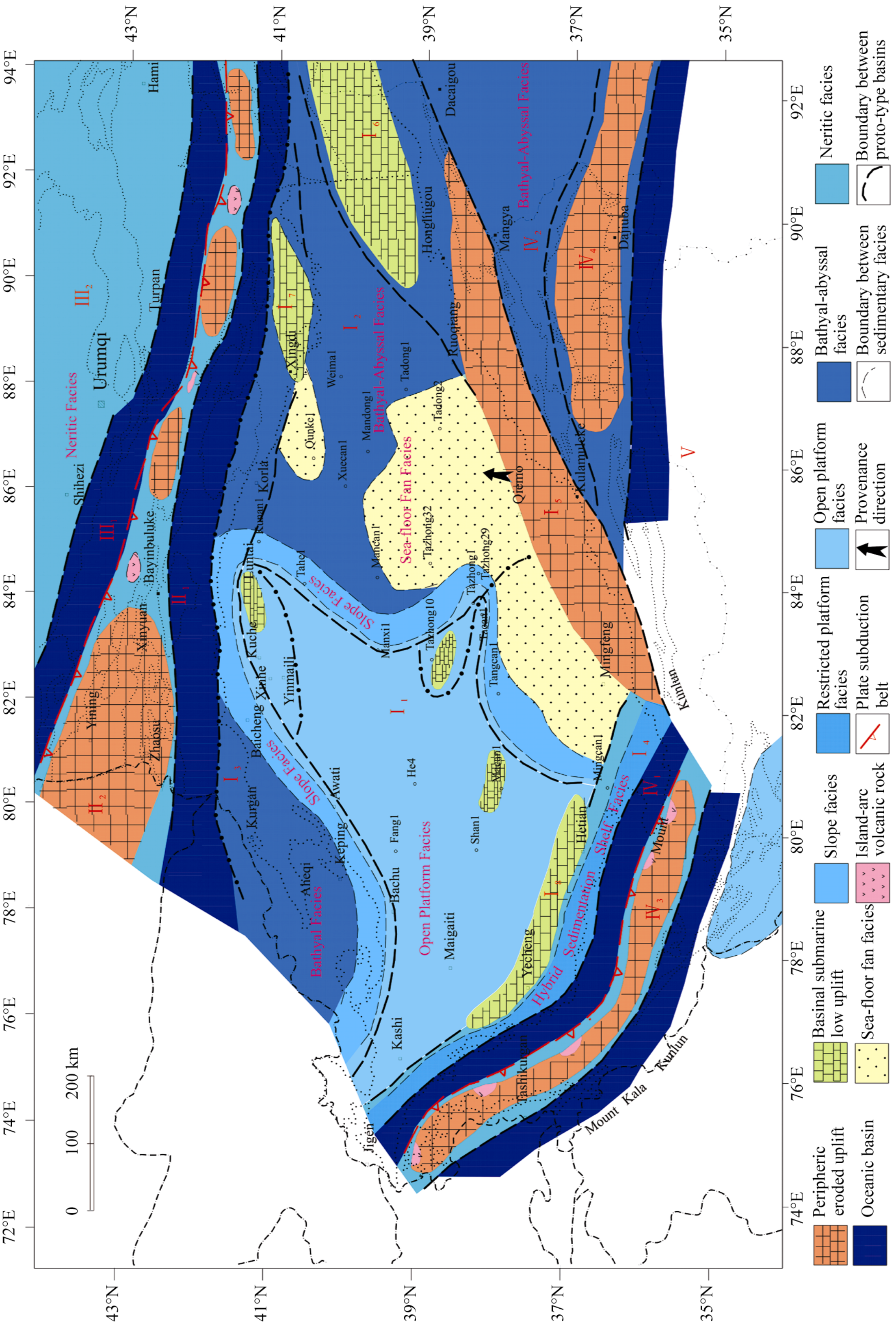

Figure 2 Middle Ordovician tectono-depositional environment of Tarim Basin and adjacent areas. I_1, West Tarim interior cratonic depression; I_2, East Tarim marginal depression; I_3, North Tarim passive continental margin basin; I_4, Southwest Tarim passive continental margin basin; I_5, Altyn Tagh uplift; I_6, Luobuzhuang uplift; I_7, Kuokesu uplift; I_8, Hetian low uplift; II_1, South Tianshan oceanic basin; II_2, Central Tianshan uplift; III_1, North Tianshan oceanic basin; III_2, Junggar-Turpan-Hami block; IV_1, North Kunlun oceanic basin; IV_2, Qimantage trough; IV_3, West Kunlun uplift; IV_2, East Kunlun uplift; V, Ancient Kunlun ocean.

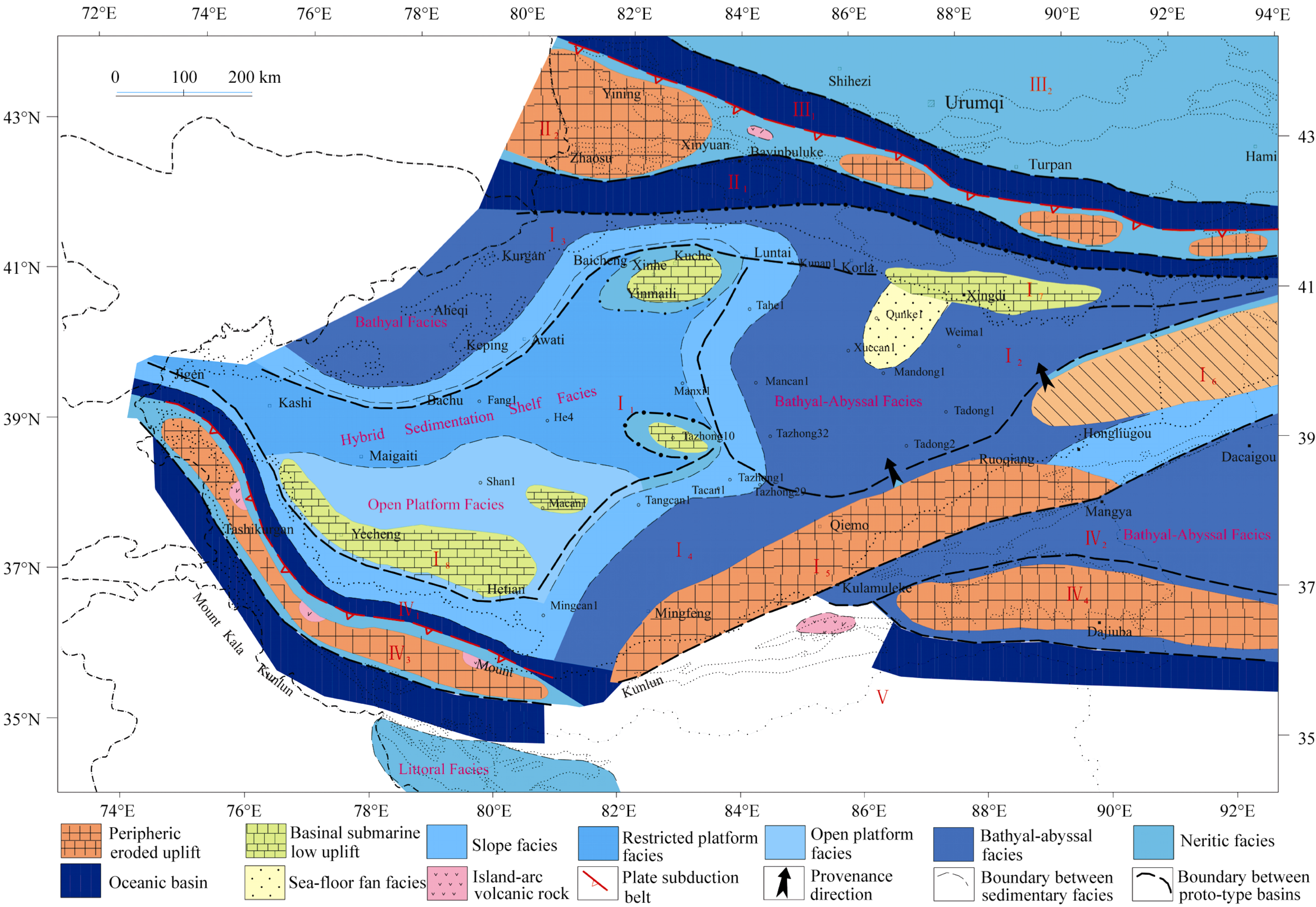

Figure 3 Late Ordovician tectono-depositional environment of Tarim Basin and adjacent areas. I_1, West Tarim interior cratonic depression; I_2, East Tarim marginal depression; I_3, North Tarim passive continental margin basin; I_4, Southwest Tarim passive continental margin basin; I_5, Altyn Tagh uplift; I_6, Luobuzhuang uplift; I_7, Kuokesu uplift; I_8, Hetian low uplift; II_1, South Tianshan oceanic basin; II_2, Central Tianshan uplift; III_1, North Tianshan oceanic basin; III_2, Junggar-Turpan-Hami block; IV_1, North Kunlun oceanic basin; IV_2, Qimantage trough; IV_3, West Kunlun uplift; IV_2, East Kunlun uplift; V, Ancient Kunlun ocean.

micrite limestone. The palaeontological assemblage was the Agnostus-graptolite assemblage. The slope zone in the southern part of the basin was different from that in the northern part of the basin. Lunnan area in the northern part developed earlier and Central Tarim area in the southern part started to acquire sedimentation in the sedimentary period of Lianglitage Formation after long-term exposure and extended westward along with the continual rise of sea level. In the early sedimentary stage of Lianglitage Formation, Wells Tazhong 24—30 zone in the outer margin of the slope was once the rimmed-like shallow beach sedimentation.

The slope zone extended southwestward to Tangguzibasi area. The Querqueke Formation ($O_{2\text{-}3}q$) at Well Tangcan1 was the thick gray and dark gray turbidite deposits. The upper part was gray and dark gray mudstone, silty mudstone interclated with siltstone and muddy siltstone of the same color. The top was interbedded with gray limestone and muddy limestone. The middle part was the interbedding of gray muddy siltstone, siltstone, dark gray silty mudstone and mudstone with the different thicknesses. The lower part was gray brown and dark gray mudstone. The bottom was dark gray limestone. The fossil was conodont, Chitinozoan and trilobite.

In the Korping-Yingmaili zone and the East Bachu-Central Tarim zone, west of the slope zone, Late Ordovician was mixed deepwater continental shelf area. The deposit was mainly dark mudstone intercalated with limestone. The area of Bachu faulted uplift was an open platform in the early stage of Late Ordovician and the mixed shallow-water continental shelf deposition in the late stage. The deposit was mainly brown sand shale intercalated with micrite limestone. Wells Fang1 and He4 were drilled 240—380 m deep into the Lianglitage Formation (O_3l). The upper part was the interlayer of mudstone and muddy limestone of the platform marginal slope sub-facies. The lower part was pure limestone of the open platform sub-facies. The Sangtamu Formation (O_3s) located above it was extensively distributed in the region with a thickness of 43.5—247 m. The lithology was calcareous marl intercalated with limestone. The calcareous content was slightly increased at the eastern end of Mazha Tagh fault structural belt.

The area of Maigaiti was a broad platform zone. The underwater low uplift developed in the Yecheng-Hetian area. The southern part was an area of the slope and submarine facies.

3 Tectonic framework and evolution

In the Ordovician period, there was the composite of the interior cratonic depression and peripheral cratonic depression. The interior cratonic depression was mainly the platform sedimentation while the peripheral cratonic depression was mainly the basin sedimentation. Significant changes took place in the framework and properties of the basin among Early Ordovician, Middle Ordovician and Late Ordovician.

3.1 Early Ordovician

Early Ordovician basin framework was basically the one inherited from the Cambrian period. North Kunlun Ocean expanded with development of southwest Tarim passive continental margin on the northern side. The amplitude and area of Hetian low uplift also expanded and once became the exposed denudated uplift. The bathyal to abyssal trough formed in the area of Qiman Tagh which was close to the southeastern margin of the basin. South Tianshan oceanic basin was already in its preliminary shape. The platform marginal slope became wider within the basin while the thickness of deposits in the West Tarim interior cratonic depression became higher. The East Tarim peripheral cratonic depression remained as under-compensated depression (Figure 1).

The tectonic movement in the end of Early Ordovician was apparent in the basin. The genesis was related to subduction of North Kunlun Ocean, Altyn Tagh Ocean and North Tianshan Ocean. Accompanied by the movement in this period, three uplifts or low uplifts — Central Tarim, Manan and Hetian — developed and unfolded in an echelon arrangement within the basin (North Tarim uplift was also in its preliminary shape). In Central Tarim area, Wells Tazhong12, 401, 162, 43 and Tacan1 were drilled through Ordovician limestone into Lower Ordovician, lack of Middle Ordovician Dawan stage, Guniutan stage and Upper Ordovician Miaopo stage, which confirmed the unconformity between Upper Ordovician and Lower Ordovician. In the area of Manjiaer depression basin facies, the seismic profile shows the obvious on-lap relationships between Middle and Upper Ordovician and Lower Ordovician limestone, referring to the tectonic movement at the end of Early Ordovician.

3.2 Middle Ordovician

Great changes took place in the framework of the basin in Middle Ordovician. The southern margin of the basin was likely to turn into the compressional regime from the extesional regime owing to the disappearing of North Kunlun Ocean and the destruction of Altyn Tagh trench-arc-basin system (Figure 2). The compressional effect, on one hand, led to folding and uplifting on the northern margin of Altyn Tagh and in Luobupo area, which became the important sources for Manjiaer depression, such as appearance of the large-scale submarine fan system. On the other hand, the compressional effect was along the Altyn Tagh zone with the possibility of sinistral squeezing. The strike-slip faulting took place in North Minfeng fault, leading to continuous development of Central Tarim and Manan uplifts. In addition, Gucheng nose uplift started to be shaped. These three NWW directional uplifts were distributed in an echelon arrangement, strengthening the relief of the landform in the interoir of the basin. The internal changes of the basin were also reflected in narrowing of the platform marginal slope, which migrated westward more than 100 km. The slope zone became NE-SW directional after it extended westward across Central Tarim area. Tangguzibasi depression was also filled with the sedimentation of the platform marginal slope facies and bathyal to abyssal facies. The West Tarim interior cratonic depression became the mixed platform thanks to appearance of the denudation zone. As compared to Early Ordovician, the thickness of the Middle Ordovician became smaller in the West Tarim platform area. On the contrary, the thickness became larger in the East Tarim peripheral cratonic depression.

Xingdi fault is the boundary between the East Tarim peripheral cratonic depression and North Tarim passive continental margin basin. The northern side of the fault was characterized in offshore platform in Early Ordovician with development of the open platform-continental shelf sedimentation with a thickness of 2410 m. Up to the Middle Ordovician, there was very stable shallow-sea carbonate platform sedimentation with a thickness of 110 m. With South Tianshan oceanic basin expanding, North Tarim passive continental margin became gradually mature in development and wider. The dwindling of North Tianshan oceanic basin accelerated expansion of South Tianshan oceanic basin. The expansion was related to the location of South Tianshan oceanic basin behind Central Tianshan island arc and the retro-arc spreading.

There was also development of mixed continental shelf in Southwest Tarim continental peripheral basin thanks to the growth of uplifts on the two sides. The continental marginal rift tectonic setting was shaped in Qiman Tagh area with deep sea water, where the deposition of clastic rock or tuff clastic rock, neutral-to-neutral acidic or basic-to-acidic volcanic rock, clastic rock and terrigenous clastic rock was accumulated with the thickness reaching 10000 m.

3.3 Late Ordovician

The basin framework in Late Ordovician inherited the features of Middle Ordovician. The platform slope continued to migrate westward with the width doubled. The uplifts or upswells of Hetian, Manan, Central Tarim and North Tarim expanded in area (Figure 3). The study of the Ordovician system in Mazha Tagh area demonstrated that there was an unconformity surface between the Middle Ordovician arene limestones and the Upper Ordovician oolite limestones, lack of intervals from the late stage of Middle Ordovician to the early stage of Late Ordovician[50].

The West Tarim interior cratonic depression was under a mixed continental shelf environment with the thickness of deposition decreasing drastically. On the contrary, the over-compensation sedimentary assemblage developed in East Tarim peripheral cratonic depression. The uplifts of Altyn Tagh and Luobuzhuang were the main sources. Continental marginal rift trough in Qimantage region was in its late stage. The volcanic activities became weakened obviously but the sea water remained deep.

3.4 Evolution of tectonic framework

The following are the characteristics of the evolution of Ordovician tectonic framework:

The basin had a “high in the west and low in the east” pattern. A slope was the transition belt between the interior cratonic depression in the west and the peripheral cratonic depression in the east. The thickness of the Early Ordovician deposition was large in the west and small in the east, but the thickness of the Middle and Late Ordovician was small in the west and large in the east. The over-compensation deposition appeared in the peripheral cratonic depression in the eastern part in Late Ordovician.

The platform marginal slope zone on the eastern side of the West Tarim interior cratonic depression experienced a narrow-wide-narrow development process. The slope constantly migrated westward and extended southwestward after it run across Central Tarim area. It formed a U-shaped pattern with the slopes on the northern side and northwestern side of the Tarim block.

The relatively dry and hot climate in Early Ordovician turned into the moist climate in Middle and Late Ordovician thanks to the changes in the movements of Tarim block (such as changes in the latitude and bearing)[51].

The "compression in the south and extension in the north" tectonic regime was gradually established, leading to the conversion from the east-west differentiation pattern to the south-north differentiation pattern in the Tarim Basin. The low uplifts or upswells formed in the basin with the amplitude enlarged. Influenced by the activities of Altyn Tagh fault system, the low uplifts or nose upswells formed and were distributed in an echelon arrangement under compression.

The West Tarim interior cratonic depression started the conversion into the mixed platform and mixed continental shelf from the open and restricted platform owing to the appearance of Late Ordovician source zones in the southern part, marking the change of basin properties. The Tarim Basin turned from the Cambrian-Ordovician "east-west differentiation" pattern to the Silurian-Devonian "south-north differentiation" pattern. The period from the Early Cambrian to Late Ordovician Wufeng stage was a large complete cycle of transgression and regression.

The passive continental margin of the northern part of the Tarim block developed gradually into maturity from narrowness to width. Xingdi fault stood between this continental margin and East Tarim peripheral cratonic depression. The formations and volcanic rock lithological assemblages of two different sedimentary environment types existed on the two sides of the fault. The area south of the fault was mainly bathyal to abyssal turbidite, radiolarian silicalite and graptolite. The volcanic rock activity was characterized by double peak. The area north of this fault was mainly the deposition of carbonate platform facies. The volcanic rock was mainly basalt.

4 Discussion of basin nature

The western part of the Tarim block was the shallow-water platform (represented by carbonates) in Early and Middle Ordovician while the eastern part was deepwater basin (represented by deepwater under-compensation black carbon-silicon lime mudstones). In Late Ordovician, the central and western parts became the mixed continental shelf while the eastern part remained as "deepwater basin" (represented by the over-compensation deepwater turbidites)[52−54]. The current discussion is focused on the mechanism for the drastic turn of this tectonic framework and the related basin nature.

Currently, there are three main typical viewpoints on the nature of the Ordovician Tarim Basin: (1) Viewpoint of "aulacogen." Jia et al.[5,6,9,34] believed that the Tarim block and its surrounding region were under the extensional tectonic regime in the Sinian-Ordovician period. The Kunlun and Tianshan regions on the southern and northern sides respectively developed into the later passive continental margin from the early rift. The rift system developed in the northeastern part of the block. This rift system extended into the northeastern part of the Tarim Basin from Beishan and South Tianshan Mountain, characterized by development of the basic and acidic "two-peak" continental rift volcanic rocks in Kuluke Tagh region in the Sinian-Early Cambrian period. Therefore, Jia et al. called it Kuluke Tagh-Manjiaer aulacogen (abbreviated as "Ku-man aulacogen"). In addition, the Late Ordovician turbidite of the submarine fan facies with a thickness of 3000—4000 m in Manjiaer region is explained as sedimentation of the "aulacogen folding period." (2) Viewpoint of rift. Li et al.[55] held the opinion that the northern depression was a continental rift basin developed on the pre-Sinian crystalline basement, starting from Early Sinian and ending in Late Ordovician. The axial zone of the rift was composed of Awati depression, Manjiaer depression and Yingjisu depression (including the southern part of Kuluke Tagh) from the west to the east and extended eastward to the region east of Luobupo. The axial position of the rift was in correspondence with the mantle uplift and the high magnetic abnormal belt. (3) Viewpoint of "cratonic basin" composite with "interior cratonic depression and peripheral cratonic depression." The scholars based this viewpoint believed that the interior cratonic depression developed in the western part of Tarim while the peripheral cratonic depression developed in the eastern part of Tarim (from the eastern part of Manjiaer to the southern part of Kuluke Tagh) with a slope transitional zone between the two depressions[7,8,10,31,32,56,57], which were obviously different in subsidence. In addition, there are also some other viewpoints about the structural properties of Ordovician (Kuluke Tagh-) "Manjiaer Region," such as "passive continental margin"[57] and "deepwater trough basin"[19,29,49].

The current disputes are sparked by the following main reasons: (1) The genesis and structural properties of the "central magnetic high" in the basin: What is the period for formation of the structural belts? Are they the split belts or tectonic magmatic rock belts between the southern and northern parts of the Tarim block? They are the main factors to unveil the background of deep position from Awati depression to Manjiaer depression. The different explanations may lead to different conceptions. (2) What was the exact bearing of the Tarim block in Cambrian-Ordovician? Did the axial zone have a south-north trend (as compared to the present-day bearing)?[51] What were its relations with South Tianshan Ocean structures and bearing? Was the Tarim block located "on the northern side of Gangwana super-continent and the southern margin of proto-Tethys Ocean" like "the terrane/island arc system of the northern zone of the central orogenic belt?"[13] It is difficult to judge the relations of time and space between the internal units of the basin and its peripheral structural belts because its palaeogeographic location and its relations with the surrounding continental blocks remained unclear. (3) Analysis of the Cambrian-Ordovician extensional structures: No large-scale normal faults were found in the Cambrian-Ordovician system on the southern and north- ern sides of Manjiaer depression except small throw fault and small-scale normal faults in Sinian. Did Manjiaer depression have development of extensional structures in Cambrian-Ordovician (particularly Cambrian-Early Ordovician)? (4) Unclear subsiding mechanism of Manjiaer depresssion: Currently, there is no quantitative simulation and mechanism analysis of the rapid subsidence taking place in Manjiaer depression in Cambrian-Ordovician. (5) The internal structural units of the Tarim block and its surrounding structural units gave rise to the "composite" properties of the basin. The drastic changes took place in the type of the basin owing to the different activities of the surrounding structural belts. For example, the transformation of the structural frame- work from Early and Middle Ordovician to Late Ordovician (Figures 1—3) led to the changes in the properties of "composite" basin.

The late-period complicated structural modification and superposition of the southern margin of the basin, including the large-scale northward thrust faulting of West Kunlun Mountain and the large-scale strike-slip faulting of Altyn Tagh fault since Middle Cenozoic, strongly changed the tectono-lithologic facies in the southern margin of the basin, making it difficult to be restored. For example, in Figures 1—3, the platform marginal slope belt was suddenly intercepted by "Altyn Tagh uplift." How did the platform marginal slope extend? Where was "Altyn Tagh uplift" located during this period of time? Those issues are related to distribution, periods, structural properties and superposed composite development of the East Tarim peripheral cratonic depression. The in-depth analyses are needed for these issues.

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