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Natural Gas Industry B xx (2016) 1–7

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Research Article

Formation stage and controlling factors of the paleo-uplifts in the Tarim Basin: A further discussion☆

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Received 4 February 2016; accepted 9 May 2016

Abstract

Various types of paleo-uplifts with different characteristics are developed in the Tarim Basin. Previously, there were multiple opinions on the pale-uplifts origins and structural evolution, so the oil and gas exploration ideas and deployment in the Tarim Basin were not developed smoothly. In this paper, regional seismic interpretation and structural analysis were carried out on the deep marine carbonate rocks in this basin based on the new seismic and drilling data. Then combined with the structural denudation results, the paleo-structural frameworks were reconstructed. And finally, the formation stage and main controlling factors of paleo-uplifts were discussed. It is shown that the Middle Ordovician is the key period when regional extension was converted to compression in this basin, so stratigraphic, sedimentary and structural differences occurred. Before the deposition of Yijianfang Fm in late Middle Ordovician, three carbonate paleo-uplifts (i.e., the Northern, Central and SW Tarim paleo-uplifts) begun to appear, and they were all broad-folded paleo-uplifts of nearly E–W striking and were formed at the same stage. The distribution and development of the Phanerozoic uplifts in this basin are restricted by the Northern and Southern Tarim basement pale-uplifts of nearly E–W striking which were developed during the Precambrian. It is indicated that all the three paleo-uplifts are compressional paleo-uplifts originated from the convergence of the southern plate margin based on the basement paleo-uplifts and they are all characterized by similar structural characteristics and inherited formation and evolution. The current differences of paleo-uplifts are controlled by multi-stage intense structural reformation since the Silurian. It is concluded that the oil and gas exploration potential is immense in the carbonate reservoirs of well-preserved deep paleo-structural zones in a larger area.

Keywords: Tarim Basin; Paleo-uplift; Basement; Formation and evolution; Controlling factor; Middle Ordovician; Marine carbonate rocks; Exploration area

Paleo-uplift is a favorable destination for hydrocarbon migration and accumulation in cratonic basin [1–4]. Recently, significant exploration breakthroughs have been successively made in the marine carbonate reservoirs, lithologic reservoirs and tight reservoirs in the paleo-uplifts in the Tarim, Ordos and Sichuan basins within China. Thereby, the formation, evolution and genesis of paleo-uplift and its control on new types of reservoirs have aroused general concern [5–9]. The largest marine carbonate oilfield and condensate gas field were discovered in the paleo-uplift in the Northern and Central Tarim Basin [10,11], implying the strategic importance of paleo-uplift in oil and gas exploration and development.

Previous studies mainly focused on the structural features, formation and evolution of the paleo-uplift. Various types of paleo-uplifts with different properties, genesis and multi-phase complicated reformation were discovered in the Tarim Basin [2–4,12–16]. The paleo-uplifts in the Tarim Basin have experienced multi-phase intense reformation. There are controversies on the genesis and tectonic evolution of paleo-

☆ Project supported by the National Major S&T Project (Grant No. 2011ZX05004 & 2011ZX05003-004) and the National Natural Science Fund Project (Grant No. 41472103).
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Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2016.05.005

uplifts due to their intense stratigraphic break, complicated tectonic deformation and poor quality of seismic data. Some scholars proposed that paleo-uplifts were formed in middle Caledonian, late Caledonian, early Hercynian or late Hercynian [2−4,12−16], in response to regional compression or regional extension. These diverse viewpoints restrain the exploration ideas and deployment.

Based on new seismic and well data, the authors conducted regional seismic interpretation and structural analysis on the deep marine carbonate reservoirs in the Tarim Basin. Combined with tectonic denudation amount, the authors reconstructed the paleo-structural framework to further identify the formation period and main controlling factors of paleo-uplifts.

1. Geological setting

The Tarim Basin, located in the northwest of China, is an ancient cratonic basin with the Precambrian crystalline basement [2], covering an area of 56 × 10^4 km^2. The Phanerozoic strata are complete in the basin [2,9]. The Cambrian−Ordovician marine carbonate strata are widely distributed [11], with an area of 24 × 10^4 km^2 and a thickness of over 2000 m. The late Ordovician−Mesozoic strata, consisting of clastic rocks, contain multi-phase unconformity surfaces and faults formed under the action of multi-cycle tectonism−deposition [2]. The Cenozoic strata are widespread in the entire basin, forming the Kuqa and SW Tarim foreland basins [2].

After multi-cycle tectonic evolution and transition, various types of paleo-uplifts with different characteristics are developed in the Tarim Basin [2,4,12,15]. It should be noted that the paleo-uplifts formed in different horizons and ages may be greatly distinct [2,4,12−16]. Regional structural interpretation and mapping results show that the Pre-Carboniferous metamorphic rocks are deposited in the SE Tarim paleo-uplift, and the Cambrian−Ordovician basinal facies mudstone is deposited in the Eastern Tarim paleo-uplift. In the Bachu uplift which was formed in the late Himalayan [2,4], the large SW Tarim Pre-Silurian paleo-uplift exists in the Maigaiti slope and its periphery [9,15] (Fig. 1). In general, there are three carbonate paleo-uplifts in the Tarim Basin, namely, Northern, Central, and SE Tarim Basin.

2. Formation period and features of paleo-uplifts

2.1. Formation period of paleo-uplifts

The interior Tarim plate was under stable weak extensional environment during the Early Cambrian [2,17,18], when extensive transgression took place and the Lower Cambrian Yuertusi Fm overlapped on the Northern and SW Tarim basement uplifts. Broad epicontinental shallow sea was formed in wide and gentle terrains of the interior plate along with the gradual rise of sea level. Afterwards, intracratonic carbonate platform was formed under W−E trending weak extension [2,17,18]. A paleogeographical pattern of “two platforms and one basin” was formed in the basin, with the Western Tarim intracratonic platform in the central−west, the East Manjiaer intracratonic depression in the central−east, and the Luoxi platform in the Luobupo area in the east [17,18].

In recent years, significant progress has been made in the study on the southern margin of the Tarim plate, revealing that the paleo-Kunlun Ocean subducted in the Early Ordovician and entered the collision phase at the end of Early Ordovician [19,20]. The study results of Altyn area show that the Tarim plate collided with the Qaidam plate in the Late Ordovician, resulting in the final closure of South Altyn Tagh ocean basin. Thereby, it is inferred that the ocean basin experienced subduction in the Early−Middle Ordovician [21]. In the Early Ordovician, although intensive tectonic movement didn't occur in the interior Tarim plate, the periphery plate entered the compression and convergent stage. However, considering the relatively lagging tectonic response of the interior plate, it is inferred that the Early Ordovician is the upper time limit for the interior Tarim plate entering into the compression stage.

The Cambrian−Lower Ordovician strata were stably distributed in the Tarim Basin. When the Middle Ordovician Yijianfang Fm was deposited, formation lithology began to obviously change [11]. In the west, the platform margin reef flat of Yijianfang Fm transited into the Saergan Fm mudstone from Bachu to Keping, directly overlaying the platform carbonate rocks of Dawangou Fm [11,18]. In the east, dark mudstone formation, equivalent to condensed intervals, occurred in the Heitu'ao Fm in the upper part of Lower Ordovician [2], overlying the Lower Ordovician carbonate rocks. In the west, the Lower Ordovician still was composed of platform carbonate rocks, indicating the differences of stratigraphic sequences. The Cambrian−Lower Ordovician Penglaiba Fm is stably distributed in the interior basin [17,18], showing inherited development features, but the Yingshan Fm deposited in late Early Ordovician−early Middle Ordovician has large variation in sedimentary thickness [11,18]. Therefore, there was difference in the interior basin in the depositional period of Yingshan Fm. The Yijianfang Fm has obviously different lithologies with underlying strata, indicating that the basin has entered a new tectonic−sedimentary environment before the deposition of Middle Ordovician Yijianfang Fm.

The sedimentary facies of the Tarim Basin presented E−W partition features in the Cambrian−Ordovician [2,11] and N−S differentiation in the Middle Ordovician [11,18]. The E−W trending high-energy facies belt of Yijianfang Fm at the southern margin of the Northern Tarim Basin was not distributed along the N−S trending Lower Ordovician platform margin belt in Lunnan−Gucheng (Fig. 2), indicating that the depositional environment changed before the deposition of Yijianfang Fm. In Central Tarim−Bachu, the Yijianfang Fm was missing, but in northern Bachu, the platform margin reef banks of Yijianfang Fm directly overlaid on the intracarbonate rocks of Yingshan Fm. In West Manjiaer, the Yijianfang Fm gradually transited into mudstone and its sedimentary facies belt was different from that of Yingshan Fm. At the end of Early Ordovician, the depositional base level of the Tarim plate significantly changed in synchronization with the global

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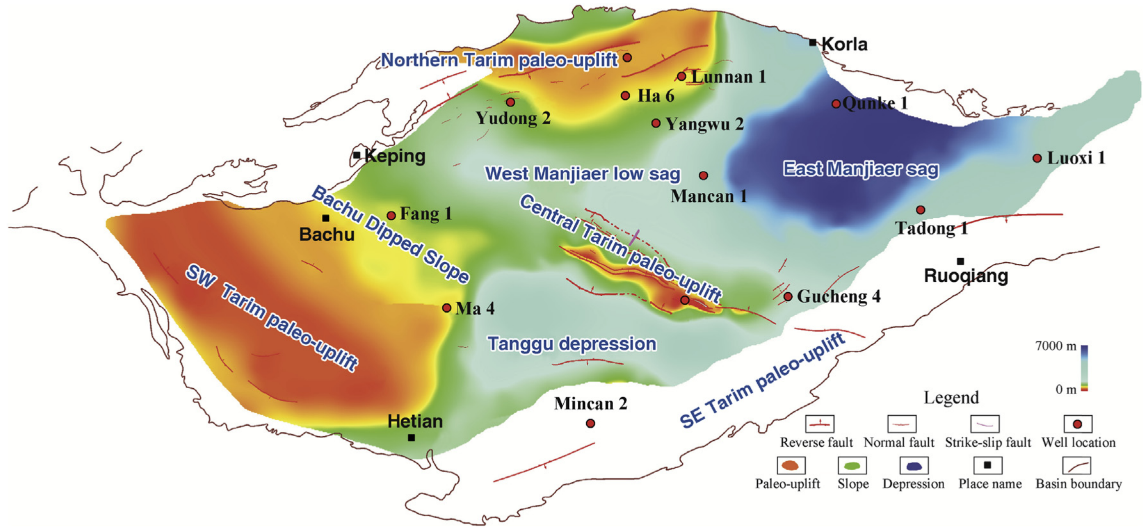

Fig. 1. Distribution of paleo-uplifts in the Tarim Basin before the Silurian deposition. (Background is the paleo-buried depth of the top surface of Ordovician carbonate rocks before Silurian. The SE Tarim paleo-uplift lacks Cambrian—Ordovician sedimentary rocks).

depositional base level [11,18]. In Middle Ordovician, the Tarim Basin underwent significant stratigraphic sedimentary differentiation. Thereby, it is inferred that the depositional period of Middle Ordovician Yijianfang Fm should be the lower time limit for tectonic regime conversion.

The Cambrian—Lower Ordovician strata are continuously distributed in the Central Tarim paleo-uplift and northern depression, while large-scale unconformity exists in the Middle—Lower Ordovician Yingshan Fm [11]. It should be noticed that the Yinghan Fm in the denuded area is much thicker than that in the footwall (Fig. 3), with a thickness difference of 300 m. Whether the thickening is resulted from deposition or tectonic movement, it is indicated that the prototype Central Tarim paleo-uplift is formed, with a stratigraphic pattern of N—S zonation. The Yijianfang Fm is distributed at the southern margin of the Northern Tarim paleo-uplift. Recent study reveals that a large river channel with N—S flow direction is developed at the top surface of Yijianfang Fm in Halahatang [22], indicating that the Northern Tarim paleo-uplift begins to form. The N—S differentiation resulted from tectonic uplifting is the basis for the significant transition of Yijianfang Fm. It can be inferred that, at the end of Early Ordovician, the prototype of Central and Northern Tarim paleo-uplifts are formed.

In summary, at the end of Early Ordovician, the tectonic setting of the Tarim Basin transited from extension to compression. In the Middle Ordovician, obvious tectonic and sedimentary differentiation occurred in the Tarim Basin. The interior Tarim Basin entered into a compressional environment before the deposition of Middle Ordovician Yijianfang Fm.

2.2. Structural features of paleo-uplift in the formation stage

In the late stage of Middle Ordovician, the paleogeographic pattern of the Tarim Basin (i.e. E—W differentiation) [18] began to differentiate. Through the reconstruction of paleostructure, it can be inferred that the structural framework of the Tarim Basin transited from a W—E platform-basin zonation to a N—S zonation (Fig. 4).

In the late stage of Middle Ordovician, the CT-I fault zone (or Tazhong-I fault zone) thrusted northeastward [23], resulting in a NW-trending large bulge [2,4]. At the same time, the Central Tarim paleo-uplift suffered an intense uplifting and erosion, resulting in the residual thickness of Yingshan Fm thinning or missing. Except for the fault zone, the Central Tarim Basin was uplifted as a whole, presenting a gentle fold and uplift. Extensive depositional break exists in the Central Tarim paleo-uplift, with the Middle Ordovician Yijianfang Fm and Upper Ordovician Tumuxiuke Fm missing [11]. The exposed Yingshan Fm carbonate rocks experienced extensive karstification, forming widespread carbonate rock weathering crust [11,23]. The activity of CT-I fault zone in the north part determined the development background of the slope break belt (Fig. 3); as a result, the sedimentary and structural boundary between Central Tarim and Manjiaer sag was formed and controlled the distribution of the large platform margin belt of Late Ordovician Lianglitage Fm [11,18].

In the SW Tarim Basin, the gentle SW Tarim paleo-uplift took its primary shape (Fig. 4), presenting an overall uplifting structural framework without faulting. Thus, a nearly E—W gentle folded paleo-uplift was formed. The Yingshan Fm was outcropped in a large area, and the Yijianfang and Tumuxiuke Fms were missing [11], forming a broad and gentle weathering crust which is integrated with that in the Central Tarim Basin. The Upper Ordovician Lianglitage Fm platform [18] was distributed within the paleo-uplift (Fig. 4). There was obvious depositional break between the platform margin reef flat of Yijianfang Fm and the underlying Yingshan Fm [11,18], indicating a gentle transitional slope belt from paleo-uplift margin to depression. In the Hetianhe gas field in the southeast, the Lianglitage Fm directly overlaid in the

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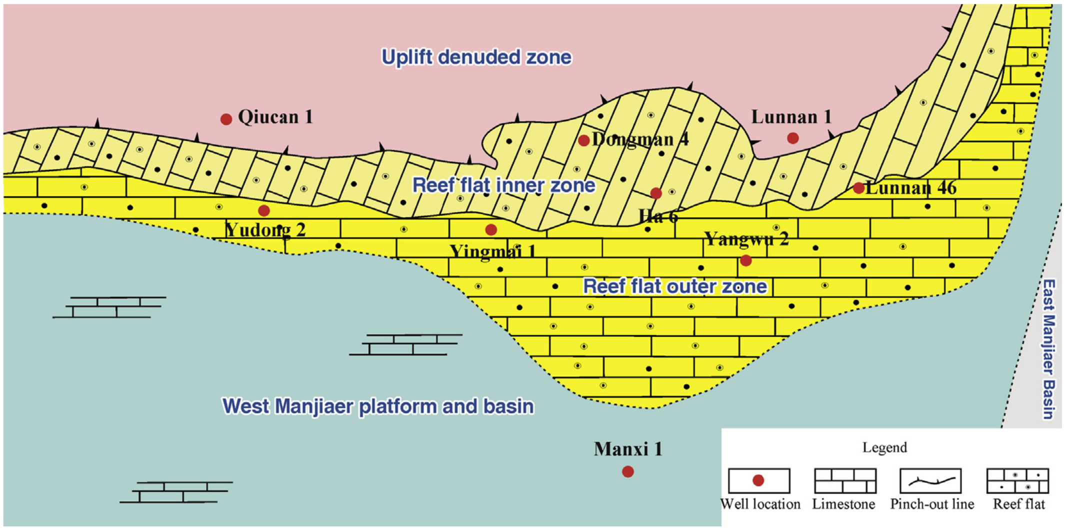

Fig. 2. Sedimentary facies of the Ordovician Yijianfang Fm at the southern margin of the northern Tarim Basin.

Yingshan Fm, and the Lianglitage Fm steep slope type platform margin was developed along the slope break belt in the paleo-uplift margin [11].

Underwater low bulge of nearly W–E trending was formed in the Northern Tarim Basin (Fig. 4). Although depositional break didn't occur, the Middle Ordovician Yijianfang Fm began to deposit around the paleo-uplift (Fig. 2), indicating that the geomorgraphy with W–E differentiation broke up. A southward paleo-channel was developed during the depositional period of Yijianfang Fm at the southern margin of the Northern Tarim Basin [23]. There was a large area of exposed zone in the axis of the Northern Tarim uplift before the deposition of Upper Ordovician, so the platform margin belt of Lianglitage Fm retrograded and migrated. The platform margin belt of Lianglitage Fm also existed at the southern margin of the North Tarim [18], which was distributed around the Northern Tarim paleo-uplift. Furthermore, there was depositional break before the deposition of Lianglitage Fm,

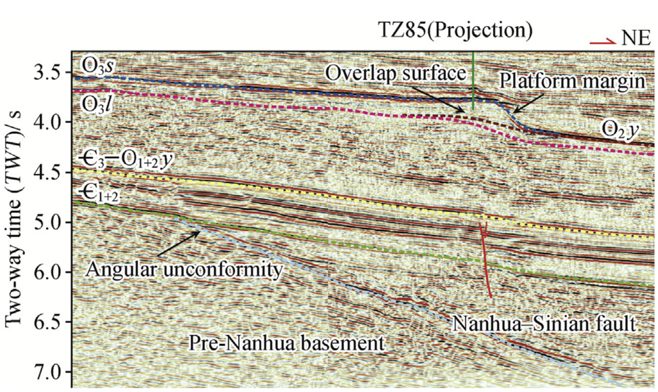

Fig. 3. N–S seismic profile through the northern part of the Central Tarim paleo-uplift. (Thicker platform margin is developed in the Upper Ordovician Lianglitage Fm. The Yijianfang and Tumuxiuke Fms are often missing in the uplift. The Lower Ordovician is thickening. The Middle–Lower Cambrian develops small normal faults and Nanhua–Sinian develops large graben faults).

indicating that the Northern Tarim paleo-uplift was formed in the late stage of Middle Ordovician. The gentle platform of Yijianfang and Lianglitage Fms was dominated by low-relief fold and uplift, a lack of high-steep slope belt and stratigraphic hiatus; underwater low bulge of nearly W–E trending was formed. There was a slight uplift exposure at the top surface of the third-order sequence [11].

Thus, in the late stage of Middle Ordovician, the Northern, Central and SW Tarim carbonate paleo-uplifts of nearly E–W trending were formed in the Tarim Basin. All of these paleo-uplifts were gentle fold uplifts, but faults were developed locally in the Central Tarim paleo-uplift. These paleo-uplifts, with flat terrain, demonstrated uplifting as a whole. The Central Tarim and SW Tarim paleo-uplifts presented higher uplifting and suffered exposure and erosion. The Northern Tarim paleo-uplift, with a low terrain, is mainly an underwater low bulge featuring continuous stratigraphic deposition.

3. Main controlling factors for paleo-uplift formation

3.1. Basement palaeo-uplift

Initially, based on limited data, the researchers usually concluded that the Cambrian directly contacted with the Sinian by continuous deposition. However, drilling data reveal that, in Northern, Central and Eastern Tarim uplifts, the Cambrian strata is observed overlaying on the Neoproterozoic–Paleoproterozoic igneous or metamorphic rocks [23], and the Sinian strata are missing. Seismic profiles also show a large-scale angular unconformity between the Cambrian and the Sinian in the Tarim Basin (Fig. 3), which is a basement paleo-uplift.

The Southern Tarim basement uplift which is high in structure was formed in the Pre-Cambrian basement of the Tarim Basin during the Keping tectonic movement [23]. Obviously, the continuous Sinian deposits are absent. The Sinian strata were seriously denudated. The truncation

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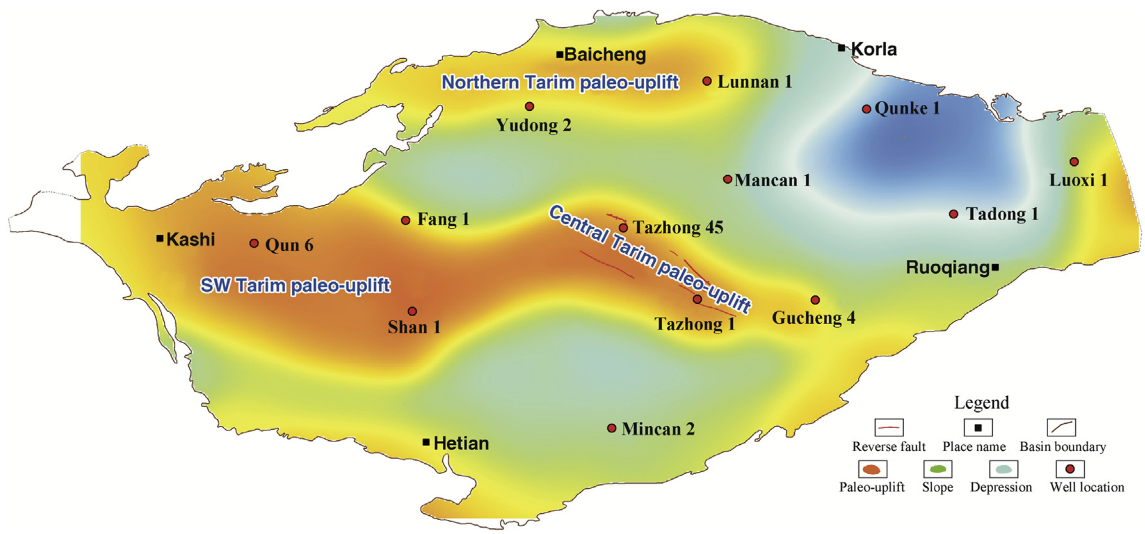

Fig. 4. Distribution of the Lower Paleozoic carbonate paleo-uplift in the Tarim Basin during Middle Ordovician epoch. (Background is the paleo-buried depth of the top surface of Middle—Lower Ordovician carbonate rocks before the deposition of Upper Ordovician Sangtamu Fm).

between Cambrian and Sinian is prominent in the Eastern Tarim [23], while in Central Tarim, the Cambrian strata overlap on the basement uplift from the north to the south (Fig. 3). The Southern Tarim uplift presents a giant basement uplift as a whole, although some small Nanhua—Sinian rifts exist in local areas. The Central Tarim inherits the structural pattern of Nanhua paleo-uplift, forming a compressional paleo-uplift of NW trending. A basement uplift is also developed in the Northern Tarim. The Sinian strata are absent in the Luntai fault uplift, so the Cambrian strata directly overlay on the Pre-Sinian metamorphic basement. It indicates that the basement of the Tarim Basin experienced tectonic uplift dominated by N—S compression before Cambrian.

Basement paleo-uplifts are mostly independent structural units, with unique lithology and rock physical properties, or are separated with the surrounding structural units by a structural weak zone [2,4,23,24]. They may easily form inherited flexure deformation during the compression at late stage, forming a reactive uplift. The Southern Tarim basement paleo-uplift, the main location where the Central Tarim and SW Tarim paleo-uplifts were developed in late stage, breaks up into several different uplift units due to the variation in stress orientation and acting form (Figs. 1 and 4). The SW Tarim paleo-uplift inherited the outline of NW-trending basement uplift (Fig. 1) when it was formed during the late stage of Ordovician. Due to intense compression, the northern boundary of the Central Tarim paleo-uplift was formed along the basement weak part of the CT-I structural belt in Middle Ordovician, controlling the distribution scope of the paleo-uplift. The boundary scope is related to the fault zone in the basement uplift [15,16]. Although the Northern Tarim paleo-uplift underwent complicated tectonic reworking in late stage [2], the W—E trending basement paleo-uplift in the periphery of the Luntai fault zone is located in the development center of the Phanerozoic uplift for a long time and controls the paleo-uplift formation and distribution at late stage.

The Tarim Basin experienced various types of tectonic movements in multiple phases and diverse patterns [2,4,12—16,25—28], such as the convergence of southern plate margin occurred during Caledonian—Hercynian and the intense Southern Tianshan closure occurred during late Hercynian—Indosinian. The current geomorphology of the paleo-uplift is significantly different from that of Middle Ordovician due to its intense tectonic reformation [2]. However, the basement paleo-uplift is stable after phanerozoic time under the control of surrounding geologic structures [2,12—16]. The Tarim Basin was subjected to an intense tectonic movement in the southwest during Silurian—Devonian. However, the outline and distribution of Southwestern, Northern and Central Tarim paleo-uplifts remained unchanged, and the Lower Paleozoic carbonate rocks still followed the structural framework of the prototype paleo-uplift [15,16]. Affected by its basement, the Northern Tarim paleo-uplift began to intensely uplift in response to the long-distance stress during Caledonian. Later, it experienced multi-phase tectonic reformation from the north part, and preserved original paleo-uplift form although the degree of reformation differed greatly depending on blocks [2,15,16]. Although paleo-uplifts existed in Keping and NE Tarim Basin [2], there were no long-term inherited uplifts due to the non-continuous development of basement uplifts and structures as well as the varying structures.

3.2. Dynamic effect

Intracratonic paleo-uplifts were usually formed due to the stress transmitting to the plate during the convergence or divergence of plate margins [2,4]. It is still controversial whether the extension of the Tarim Basin at early stage controlled the paleo-uplift formation and distribution.

An analysis reveals that the Tarim Basin, with a Pre-Nanhua crystalline basement [2,23], contains large intracratonic platforms and basinal deposits which have deposited since the Cambrian, under a weak extensional and stable tectonic setting [18]. The seismic data and well data newly acquired in recent years show that the paleo-uplift areas lack large stretching structures and fault uplifts formed from extension rifts. The latest seismic data reveal that the CT-I fault is a large thrust fault formed during the Middle Ordovician [15]. In the east, the fault extends to the top surface of Middle–Lower Ordovician Yingshan Fm upward and the basement downward, without large normal faults. In the west, although minor normal faults are developed in Cambrian (Fig. 3), stratigraphic deposition is continuous and has no control on paleo-uplift scale. Under the stable intracratonic weak extensional tectonic setting (Fig. 5-a), the basin represents E–W sedimentary differentiation. The Central, Northern and SW Tarim paleo-uplifts are E–W trending, inconsistent with the E–W trending extensional background. Thereby, extension is not the main controlling factor for the formation of paleo-uplifts.

At the end of Early Ordovician, the southern Tarim Basin transited from passive continental margin to active continental margin [2,20] (Fig. 5-b). Under the intense regional extrusion, the intraplate basement paleo-uplift of nearly W–E trending is in the stress concentration region. Thin overlying sedimentary cap rocks suffered an intraplate flexure deformation due to the regional compressional stress and the sedimentary load, which is favorable for the formation of compressional paleo-uplifts. As the regional compression increased at the southern margin of the plate, the Central and SW Tarim basement paleo-uplifts began to uplift while flexing, forming the Bachu–Central Tarim front uplift (Fig. 4). Affected by long-distance compressional stress, the old cratonic crust was subjected to only weak folding deformation. As a result, the Yijianfang Fm limestone was extensively and stably distributed, with a thickness of less than 100 m [11,18], indicating a low relief paleogeomorgraphy. The northern Tarim Basin was still in a discrete state. However, the basement paleo-uplift was reactivated to form the prototype uplift of W–E trending, due to the collision at the southern margin. The Kuqa underwater low bulge with thin thickness and N–E trending distribution

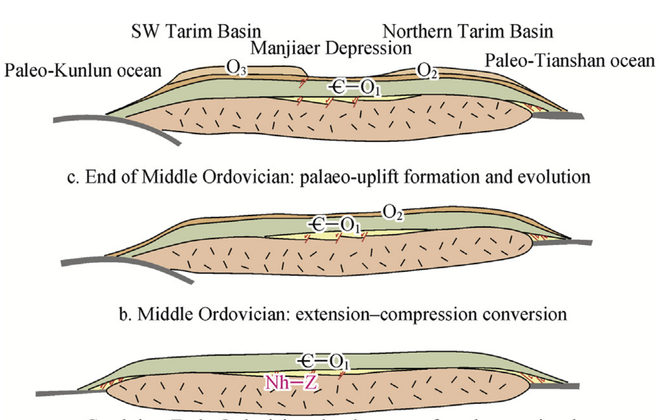

Fig. 5. Formation and evolution model of paleo-uplifts in the Tarim Basin.

was developed at the margin of the Northern Tarim–Kuqa plate, which controls the sedimentary distribution of Yijianfang Fm.

Comprehensive analysis reveals that the interior Tarim plate entered the regional compressional stage during the Middle Ordovician. On the basis of basement paleo-uplift, the Bachu–Central Tarim back-arc front paleo-uplift and the Northern Tarim underwater low bulge were developed (Fig. 4). Moreover, the Lower Paleozoic carbonate palaeo-uplift took its primary form. These compressional paleo-uplifts laid a foundation for the development of the Northern, Central and SW Tarim paleo-uplifts.

During the Late Ordovician, the Altyn ocean was closed and subducted, and the island arc activity was intense [2,21]. Besides, the tectonic compression in the south became intense and the arc-continent collision occurred in the southeastern direction, contributing to the formation of the carbonate palaeo-uplift within the Tarim Basin (Fig. 5-c). The EW-trending depression begun to form in the West Manjiaer area, and the Northern and Central Tarim were separated. In the south, the SW Tarim paleo-uplift was separated from the Central Tarim paleo-uplift by the Bachu low bulge. The Ordovician carbonate rocks in the vicinity of the plate margin were outcropped in a large area in the NW-trending SW Tarim paleo-uplift due to intense tectonic uplifting, spreading in a consistent manner with the basement uplift. The Central Tarim Basin has a structural pattern of "high in the east and low in the west" under the EW-titling movement. A large area of Ordovician carbonate weathering curst occurred in the east [11]. The morphology of NW-trending Ordovician carbonate paleo-uplift kept unchanged since folding took place in N–S direction and intense uplifting took place in the central part, gradually weakening southwards and northwards. Folding and uplifting also took place in the Northern Tarim area, so a slope was developed in the south part and the West Manjiaer sag, and the Silurian overlapped on the top surface of Ordovician carbonate rocks. The Lower Paleozoic carbonate rocks were outcropped in a large area in the Northern Tarim Basin. Thereby, the Central, Northern and SW Tarim paleo-uplifts were basically finalized in the Late Ordovician (Fig. 1), with the Lower Paleozoic carbonate rocks dominated by inherited folding uplifts.

Since the Silurian, the paleo-uplifts had experienced multi-phase tectonic reformation, resulting in significant variation in internal structures [2,12–16]. However, the Cambrian–Ordovician marine carbonate paleo-uplift inherited the morphology and structure of pre-Cenozoic paleo-uplift [11,15], which was favorable for hydrocarbon migration, accumulation and preservation [11]. Hydrocarbon might not be only accumulated in the present exploration scope (2×10^4 km^2) of Northern and Central Tarim Basin, since the paleo-uplifts were formed earlier, with excellent spatial–temporal collocation. Therefore, the widely-developed carbonate rocks with good preservation conditions in deep zones in paleostructures have a great exploration potential.

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4. Conclusions

1) The Northern, Central and SW Tarim marine carbonate paleo-uplifts began to form during the Middle Ordovician. All of them are gentle folded uplifts.
2) The paleo-uplifts in the Tarim Basin, restricted by the basement paleo-uplift, are compressional paleo-uplifts formed on the basement paleo-uplift due to the convergence occurred in the plate southern margin. They demonstrate inherited formation and evolution.

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Please cite this article in press as: Neng Y, et al., Formation stage and controlling factors of the paleo-uplifts in the Tarim Basin: A further discussion, Natural Gas Industry B (2016), http://dx.doi.org/10.1016/j.ngib.2016.05.005