Journal of Petroleum Science and Technology 11(1): 29, 2021, Pages 35-42
DOI:10.22078/jpst.2021.4387.1709

Journal of Petroleum Science and Technology

https://jpst.ripi.ir/

Evolution and Hydrocarbon Accumulation of the Cambrian-Ordovician Paleo-uplifts in the Southwest Tarim Depression, China

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Abstract
There is a close relationship between the evolution of the Cambrian–Ordovician paleo-uplifts and their hydrocarbon accumulation in the Southwest Tarim Depression. Using regional 2D seismic data interpretation, the structural morphology of the top of the Ordovician carbonate rocks in the Southwest Tarim Depression at different historical geologic stages is mapped. Combined with analysis of the discovered oil and gas reservoirs, the regularity of the hydrocarbon distribution in the Southwest Tarim Depression is investigated. Research shows that the evolution of the Cambrian-Ordovician paleo-uplifts in the Southwest Tarim Depression can be divided into four stages: (1) formation of the paleo-uplifts, (2) steady subsidence of the eastern paleo-uplift, (3) migration and adjustment of the western paleo-uplift and (4) strong subsidence and extinction of the paleo-uplifts. The Cambrian-Ordovician strata in the Southwest Tarim Depression experienced a seesaw-like structural reconstruction from an early north-dipping slope to a late south-dipping slope. During the structural reconstruction process, a pivot zone was located at the position of the current Maigaiti Slope, proving favorable for hydrocarbon accumulation and preservation. The fault zones in the eastern and western paleo-uplifts of the Maigaiti slope finalized during the Late Hercynian Period were favorable to preserving paleo-oil reservoirs. In contrast, the fault zones in the northern margin of the Maigaiti Slope, where the current tectonic uplift is located, were favorable for the accumulation of gas reservoirs.

Keywords: Paleo-uplift, Paleo-oil Reservoir, Lower Paleozoic, Maigaiti Slope, Southwest Tarim Depression

Introduction
The term "paleo-uplift" usually refers to an uplift structure formed at a historical geological stage during the formation and evolution of a basin [1–3]. Large oil and gas fields have been found in many paleo-uplifts of craton basins all around the world [4–8]. The Tarim Basin in northwestern China has experienced multiple stages of tectonic movement in its geological history, and it has developed paleo-uplifts of various types and characteristics [9–10]. The Lower Paleozoic paleo-uplifts in the Tabei and Tazhong areas are stable paleo-uplifts, in which the discovery of marine carbonate oil and gas fields confirmed the control of hydrocarbon migration and accumulation by stable paleo-uplifts [10–14]. The Lower Paleozoic paleo-uplift in the Southwest Tarim Depression is characterized by strong tectonic activity, and it has experienced multistage movement and adjustment [15–18]. The tectonic properties of the paleo-uplifts in the Southwest Tarim Depression were first thought to indicate an active paleo-uplift [8]. Some scholars have argued that the degraded paleo-uplifts in the Southwest Tarim Depression have no exploration value because they currently do not possess an uplifted structure [12]. However, this view neglects that the lithologic and stratigraphic reservoirs could be formed and preserved during the evolution of such paleo-uplift The research on the geological structure and hydrocarbon accumulation of the paleo-uplift in the Southwest Tarim Depression has reached many useful results. However, there are some different points of view regarding the structural evolution and control of hydrocarbon accumulation, owing to the limited degree of oil and gas exploration in this area. By making full use of 2D seismic data for the Southwest Tarim Depression, the structural morphologies of the tops of Cambrian and Ordovician strata in different geological periods have been restored, which reveals the evolution of the paleo-uplifts in the study area. Using the results of various oil and gas

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Received 2021-01-14, Received in revised form 2021-06-17, Accepted 2021-08-03, Available online 2021-10-10

reservoir investigations, the regularity of the hydrocarbon distribution of the study area is discussed, which provides a reference for hydrocarbon exploration.

Geological Setting

The Southwest Tarim Depression is a Cenozoic foreland depression developing on the Precambrian crystalline basement of the Tarim plate [14]. It can be divided into four second-order structural units, namely the Kashgar Sag, the Yecheng Sag, the Hetian Sag, and the Maigaiti Slope (Fig. 1(a)). The Bachu Uplift bounds it to the northeast, the Tangguzibasi Depression to the east, and the Keping fault block to the northwest. The Paleozoic strata in the Southwest Tarim Depression can be divided into four sequences:(1) Cambrian-Ordovician marine carbonates and evaporites, (2) Silurian-Devonian Marine clastics, (3) Carboniferous marine clastics and carbonates, and (4) Permian terrestrial clastics and volcanics (Fig. 1(b)).

Two potential source rocks are present in the Southwest Tarim Depression, including the Lower Cambrian Yuertusi Formation ($\in_{1y}$) marine shale and the Lower Carboniferous Bachu Formation (C_{1b}) marine muddy limestone [19-21]. The $\in_{1y}$ marine shale, characterized by high organic matter abundance and high-degree of thermal evolution, is confirmed as the dominant source rock in the Southwest Tarim Depression [20-23]. This source rock has experienced two hydrocarbon-generation stages: the Hercynian Period (323–248 Ma) for a large amount of oil generation and the Himalayan Period (from 66.7 Ma to the present) for the gas generation [20-22]. The C1b muddy limestone, characterized by medium organic matter abundance and low degrees of thermal evolution, is confirmed as a lack of large-scale hydrocarbon generation [19].

The Middle Cambrian Awatage Formation ($\in_{2a}$) gypsum-salt, which is regionally distributed in the Southwest Tarim Depression, played a role in separating the subsalt hydrocarbon migration and accumulation from the post-salt one. The reservoir-cap rock assemblage of the sub-salt petroleum system is composed of the Lower Cambrian Xiaoerbulake Formation ($\in_{1x}$) dolomite reservoir and the $\in_{2a}$ gypsum-salt cap. Whereas, there are several reservoir-cap rock assemblages developed in the post-salt petroleum system, including the Middle Ordovician Yingshan Formation (O_{2y}) limestone reservoir and the Lower Silurian Kepingtage Formation (S_{1k}) mudstone cap, the Upper Devonian Donghe Formation (D_{3d}) sandstone reservoir, and the Lower Carboniferous Bachu Formation (C_{1b}) mudstone cap, C_{1b} bioclastic limestone reservoir and the Lower Carboniferous Kalashayi Formation (C_{1k}) mudstone cap, the C_{1k} sandstone reservoir and the C_{1k} mudstone cap, the Upper Carboniferous Xiaohaizi Formation (C_{2x}) limestone reservoir and the Lower Permian Aquia Formation (P_{1a}) mudstone cap (Fig. 1(b)). Five oil and gas reservoirs have been discovered, namely the HT gas field, the NS gas reservoir, the YSD gas reservoir, the BSTP oil reservoir, and the YB oil reservoir, and these are distributed in the fault zones of the Maigaiti Slope (Fig. 1(a)). The NS gas reservoir and the YB oil reservoir have been found with only one set of hydrocarbon-bearing strata, which are O_{2y} limestone.The other three reservoirs have all been found with multiple hydrocarbon-bearing strata. The hydrocarbon-bearing strata of the YSD gas field and the BSTP oil field are D3d sandstone and C1b bioclastic limestone. In contrast, the hydrocarbon-bearing strata of the HT gas field are O_{2y} limestone, C_{1b} bioclastic limestone, and C_{1k} sandstone.

Materials and Methods

Tectonic Evolution Characteristics of the Paleo-uplifts of the Southwest Tarim Depression

Activation of the Cambrian-Ordovician paleo-uplifts in the Southwest Tarim Depression was closely correlated with the tectonic evolution of the southern and northwestern margins of the Tarim block [14,15].

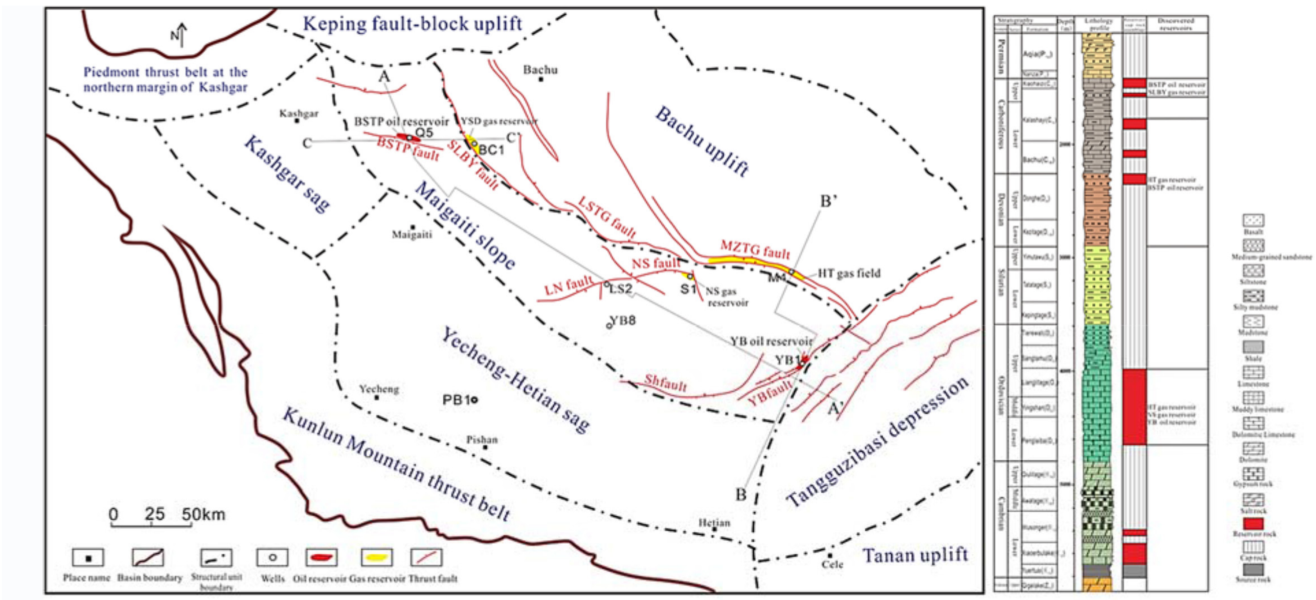

Fig.1: a) Structural division and b) comprehensive stratiographic column of the Southwest Tarim depression.

During the Mid-Late Ordovician, the Northern Kunlun Ocean at the southern margin of the Tarim Block dived below the Middle Kunlun block, which resulted in large-scale uplifting and erosion of the Middle and Upper Ordovician strata in the Southwest Tarim Depression. At the end of Silurian, the Kudi Ocean was completely closed, and the Central Kunlun island arc collided and became joined with the Tarim plate. It extensively uplifted the southeastern part of the research area resulting in erosion of all the Silurian strata. During the Devonian, the Paleo-Tethys Ocean formed at the southern margin of the Tarim block and began to dive down into the block in the Early Carboniferous. Accordingly, the Late Paleozoic island arc of the Western Kunlun was formed. During the Late Carboniferous–Triassic, the South Tianshan island arc at the northwestern margin of the research area continually collided and joined with the Tarim plate, resulting in the uplifting of the northwest part of the research area, and thereby, in erosion of the Upper Permian strata. At the end of the Triassic, the Qiangtang geological body collided with and intruded into the Eurasian plate, which resulted in the absence of Triassic strata in the research area. During the Jurassic-Quaternary, the evolution and degradation of the Neo-Tethys Ocean altered the Paleozoic structural framework of the research area. In this research, the Cambrian-Paleogene seismic sequences in Southwest Tarim Depression are interpreted using regional 2D seismic data (Fig. 2). The paleo structure of the top of the Ordovician strata at different geological times is mapped in Fig. 3.
The map reveals the structural evolution of the Cambrian-Ordovician paleo-uplifts in the Southwest Tarim Depression.

Formation Stage

The Cambrian- Ordovician paleo-uplift in the Southwest Tarim Depression was formed during the middle Caledonian Period, which included two episodes of tectonic movement. Episode I occurred at the end of the Middle Ordovician—the beginning of the Late Ordovician. Under compression from the southern margin of the Tarim plate, the Cambrian-Middle Ordovician strata in the Southwest Depression were uplifted as a whole, which resulted in common erosion of the O_{2y} strata. The preliminary paleo-uplift was distributed in the Kashgar-Yecheng-Hetian sag, spreading in an approximately E–W direction (Fig. 3(a)). Episode II occurred at the end of the Late Ordovician. The compression from the western segment of the southern margin of the Tarim plate was stronger than that from the east, leading to the uplift of the western segment of the research area and the erosion of the Upper Ordovician Lianglitage Formation (O_{31}) strata from east to west. The E-W trending seismic profile (Fig.2(a)) shows that the O_{31} strata induced thinning by erosion from east to west and pinch-out at the middle of the Maigaiti Slope. Consequently, the western segment of the research area developed a weathering crust of O_{2y} strata, whereas the eastern segment of the research area developed a weathering crust of O_{31} strata. The differentiated tectonic evolution of the Cambrian-Ordovician paleo-uplifts at the eastern and western segments of the research area began afterward.

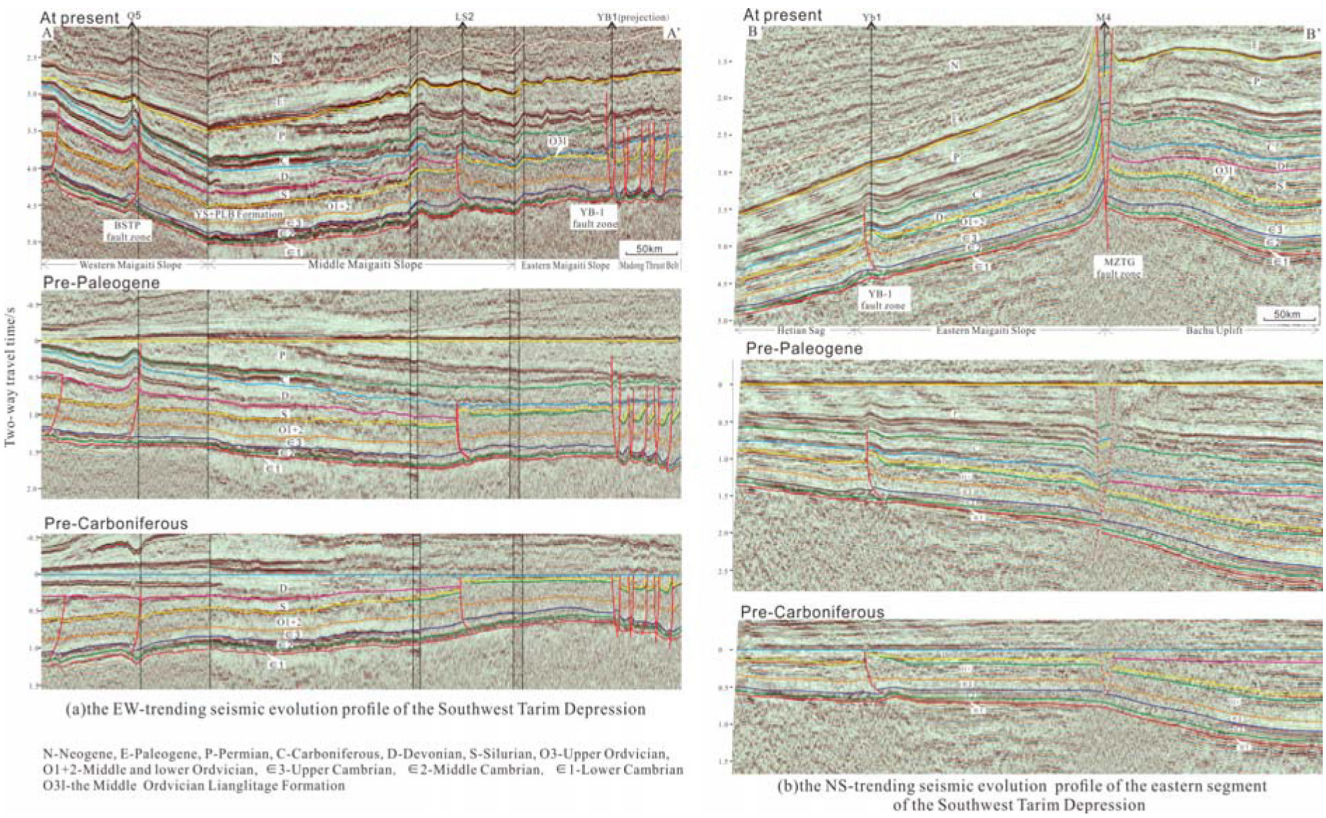

Fig. 2: Sciesmic evolution o sections in the southwest Tarim depression (the sections position refers to Fig. 1.

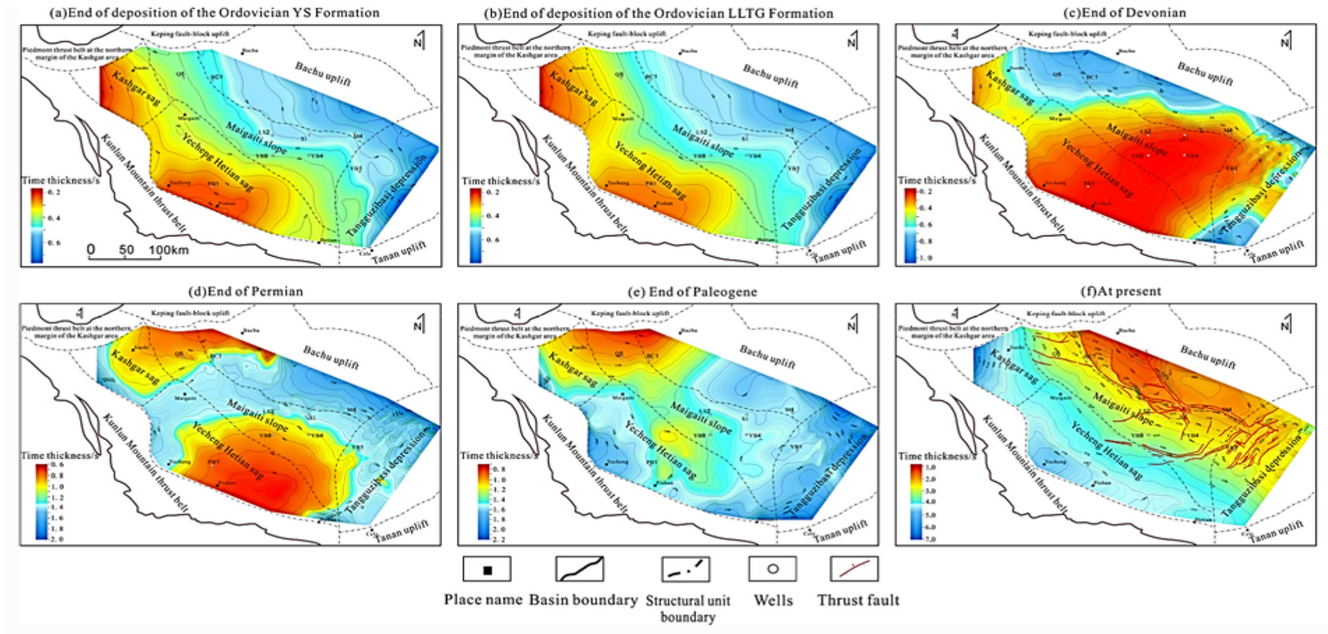

Fig. 3: Structural maps of the top of the Ordovician carbonate rock at different geological times in the Southwest Tarim depression.

Steady Subsidence Stage in the Eastern Segment

During the Silurian-Devonian, continuous compression from the southern margin of the Tarim plate led to the extensive development of paleo-uplift in the eastern segment of the Southwest Tarim Depression. The paleo-structure map of the top of the Ordovician strata at the end of the Devonian shows that the Cambrian- Ordovician paleo-uplift in the western segment of the Southwest Tarim Depression extended from the Hetian sag to the northern margin of the Maigaiti Slope, with an NNE distribution, covering an area of 5.1×104 km^2 (Fig. 3(c)).

The E-W trending seismic evolution profile of the Southwest Tarim Depression (Fig.2(a)) shows that the Silurian and Devonian strata overlapped on this paleo-uplift, thinning from west to east and pinching out at the middle of the Maigaiti Slope. The N-S trending seismic profile of the eastern segment of the Southwest Tarim Depression (Fig.2(b)) shows that the Silurian and Devonian strata overlapped on this paleo-uplift thinning from north to south and pinching-out at the eastern segment of the Maigaiti Slope. The above analysis of the seismic profiles indicates that the Cambrian-Ordovician paleo-uplift in the research area was subaqueous during the Late Caledonian-Early Hercynian.

During the Silurian-Devonian, the Cambrian-Ordovician paleo-uplift in the western segment of the research area was distributed at Kashgar Sag with a smaller development scale than the eastern segment and area of only 5300 km^2 (Fig. 3(c)).

Migration and Adjustment Stage in the Western Segment

Since the Late Carboniferous, the Paleozoic strata in the northwest of the Southwest Tarim Depression were gradually uplifted by the continuous compressive tectonic movements in the northwestern margin of the Tarim Plate. At the end of the Permian, the Paleozoic strata in the western segment of the research area had changed from a north-dipping slope to a south-dipping slope, and the Cambrian-Ordovician paleo-uplift in the western segment of the research area moved toward the north from the Kashgar Sag to the Keping fault block (Fig. 3(d)). The E-W trending seismic evolution section in the Southwest Tarim Depression (Fig.2(a)) shows that the Carboniferous and Permian strata in the western segment of the research area were eroded and thinned from southwest to northeast.

The structural morphology of the Cambrian-Ordovician paleo-uplift in the eastern segment of the Southwest Tarim Depression shows no considerable change during the Carboniferous-Permian, which still presented as a large north-dipping, paleo-uplift (Fig. 3(d)). The N-S trending seismic evolution profile in the eastern segment of the Southwest Tarim Depression (Fig.2(b)) shows that the Carboniferous strata overlapped on this paleo-uplift, thinning from north to south, and the Permian strata eroded and thinned from north to south.

Strong Subsidence and Extinction Stage

The Late Himalayan Period was characterized by intensive subsidence and degradation of the paleo-uplifts in the Southwest Tarim Depression. At the end of the Paleogene, the paleo-uplift in the western segment of the Southwest Tarim Depression still developed at the Keping fault block. In contrast, the structural tops of the paleo-uplift in the eastern segment moved to the middle of the Maigaiti slope (Fig. 3(e)). Since the Neogene, the structural tops of the eastern paleo-uplift began to move gradually northwards, and this process continued until the Neogene Pliocene. Before the Quaternary sedimentation, the Cambrian-Ordovician strata in the Southwest Tarim Depression evolved into a large south-dipping slope, and the paleo-uplifts vanished (Fig. 3(f)).

Regularity of the Paleozoic Oil and Gas Distribution in the Southwest Tarim Depression

Tectonically-stable zone was the favorable one for hydrocarbon accumulation and preservation

The Paleozoic strata in the Southwest Tarim Depression have experienced a structural reversal, changing from an early north-dipping slope into a late south-dipping slope. Therefore, the enrichment and preservation conditions for hydrocarbons during the reconstruction process were worse than those of a steadily growing paleo-uplift. However, during this reconstruction process, a zone existed that was relatively tectonically stable, and this was located at the position of the current Maigaiti Slope along the N-S direction, and served as a pivot zone for the structural reversal (Fig. 4). This pivot zone has favorable reservoir-forming conditions. First, the pivot zone of the Cambrian-Ordovician strata developed a large number of vuggy carbonate reservoirs, which favored the formation of lithologic reservoirs. Second, whether the slope was north-dipping or south-dipping, the pivot zone has always been on the migration path of oil and gas toward the structural top of the uplift. It favored the capture of oil and gas, especially in carbonate strata. Third, the pivot zone was not at the structural top of the uplift, which avoided damaging the paleo-oil reservoir at the structural top, promoting paleo-oil reservoir preservation. Noticeably, all the Paleozoic oil and gas reservoirs in the Southwest Tarim Depression are located within this pivot zone.

Regularity of Paleo-oil Reservoirs Distribution

Hydrocarbon-accumulation-stage analysis of the Lower Paleozoic oil and gas reservoirs in the Southwest Tarim Depression shows that the Late Hercynian Period was the key period for paleo-oil reservoir formation. During this formation, a paleo structural framework controlled the lateral migration of the first-formed hydrocarbons. The eastern paleo-uplift in the southwestern Tarim Depression steadily developed during the Late Caledonian-Indosinian Period, and the western paleo-uplift was formed at the end of the Early Permian and steadily developed until the end of the Cretaceous. The two major paleo-uplifts originated early hydrocarbon accumulation and controlled the formation and distribution of paleo-oil reservoirs.

The paleo-uplifts in the western and eastern segments of the Maigaiti slope were widely developed with multistage active fault zones, and these can be roughly divided into the Late Caledonian-Early Hercynian and the Late Hercynian [18]. The faults that were finalized in the Late Caledonian to the Early Hercynian Period were mainly distributed in the MD thrust belt (Fig. 1), comprising five rows of thrusting faults that were nearly parallel in the NE direction (Fig. 2(a)). The faults finalized in the late Hercynian Period mainly include the BSTP fault in the western segment of the Maigaiti slope and the SH and YB faults in the eastern segment (Fig. 1).

Paleo-oil reservoirs were found in the fault zones formed in the late Hercynian period, which indicates that the fault activity in this period controlled the formation of structural traps and the vertical migration of hydrocarbons. The YB oil reservoir in the YB fault zone (Fig. 5(a)) have developed only one set of hydrocarbon-bearing strata , which are O_{2y} limestone. The BSTP oil reservoir in the BSTP fault zone (Fig. 5(b)) comprises hydrocarbons in D_{3d} sandstone, C_{1b} bioclastic limestone, and C_{2x} limestone.

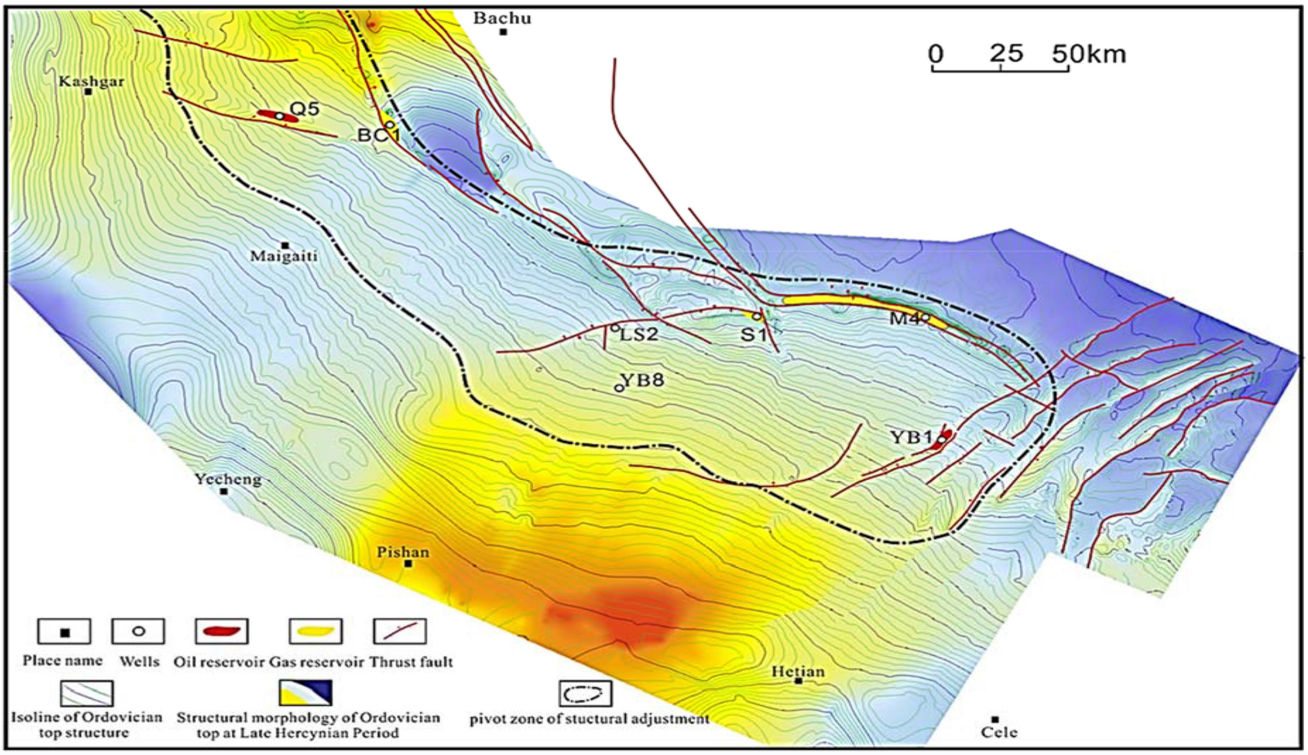

Fig. 4: Superimposed map of paleo-structure and present structure in the Southwest Tarim depression.

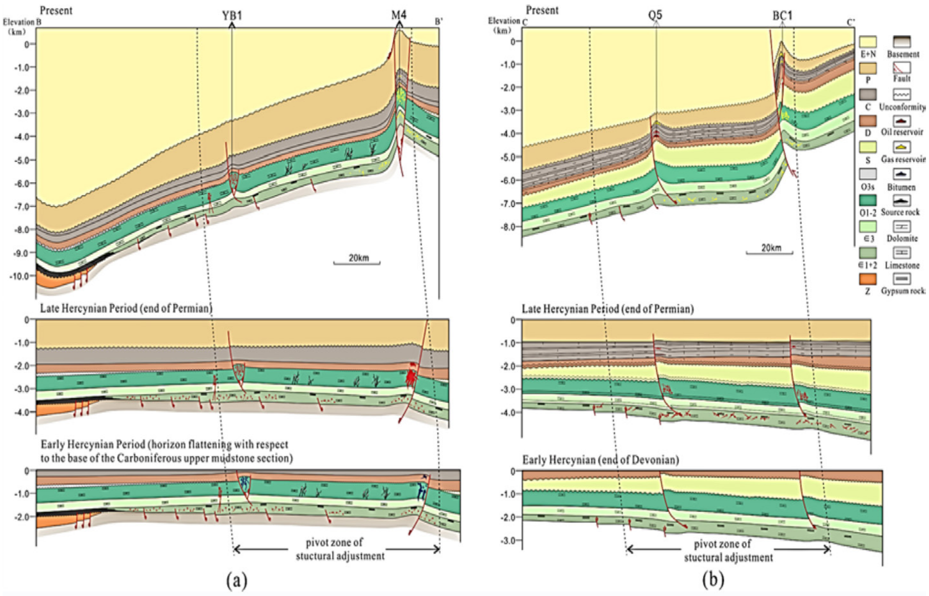

Fig. 5: Oil and gas reservior evolution sections of the east (a) and west (b) of the Maigaiti Slope (The section position refers to Fig . 1.

Although the YB and BSTP oil reservoirs had different hydrocarbon-bearing formation series, they shared an identical hydrocarbon accumulation pattern: the oil generated from $\in_{1y}$ source rock during the Late Hercynian Period, laterally migrated toward the structural tops of the paleo-uplifts and accumulated in Ordovician and Carboniferous traps by fault-through vertical migration. The paleo-oil reservoirs in the structural traps, finalized during the Late Hercynian Period, were well preserved during the structural reconstruction process in the Late Himalayan Period.

Regularity of Later Gas Reservoirs Distribution

The Cambrian sub-salt strata in the Southwest Tarim Depression were buried rapidly and deeply in the late Himalayan Period, leading to a large amount of cracking gas from the Cambrian sub-salt palaeo-oil reservoirs and $\in_{1y}$ source rock [19-22]. The HT gas field, the NS gas reservoir, and the YSD gas reservoir with considerable reserves have been discovered in the Southwest Tarim Depression, proving that there are abundant cracking gas resources in this area. The geochemical characteristics of these gas reservoirs demonstrate that the natural gas all originates from the Cambrian sub-salt strata, consisting of both oil-cracking gas and kerogen-cracking gas [19–22].

The present tectonic framework of the Paleozoic strata in the Southwest Tarim Depression is characterized by a south-dipping slope. The northern margin of the Maigaiti slope, where the current tectonic uplift area is located, originated later in gas accumulation. The faults formed in the late Himalayan Period in the northern margin of the Maigaiti slope were widely developed, including the SLBY, NS, and MZTG faults (Fig. 1). The formation mechanisms and evolution of these three faults are similar to some extent; all of them are basement-involved faults under the near north-south compression stress field in the Himalayan Period [14]. Taking the MZTG fault zone as an example, this consists of a north-dipping main fault and a south-dipping recoil fault, and the breaking horizon is the Precambrian to Neogene strata (Fig.2(b)). According to the stratigraphic distribution on both sides of the MZTG fault zone, it can be concluded that the fault activity of the MZTG fault zone began in the late Hercynian, and its previous fault morphology is difficult to recognize because of later continuous tectonism.

Hydrocarbon exploration has confirmed that the fault zones in the northern margin of the Maigaiti slope were favorable for gas enrichment. The HT gas field was discovered in the MZTG fault zone in the east of the northern margin of the Maigaiti Slope (Fig. 5(a)). It has multiple gas-bearing sections, including O2y limestone, C1b bioclastic limestone, and C1k sandstone. The YSD gas reservoir is located in the SLBY fault zone in the west of the northern margin of the Maigaiti Slope (Fig. 5(b)).

This reservoir is mainly composed of two gas-bearing sections, C_{1b} bioclastic limestone and C_{1k} sandstone, which are also stacked vertically over each other. The gas reservoirs in the northern margin of the Maigaiti slope share a gas accumulation pattern: the cracking gas originated from the Cambrian subsalt paleo-oil reservoirs of the Maigaiti Slope during the Late Himalayan Period, migrated toward the northern margin of Maigaiti slope, and vertically moved through the steeply-included thrust fault, accumulated in Ordovician and Carboniferous traps to form a secondary gas reservoir.

Results and Discussion

The oil and gas reservoirs discovered in the Southwest Tarim Depression are secondary oil and gas reservoirs, that were the products of vertical migration and accumulation of oil and gas through faults. The secondary oil reservoirs in the Southwest Tarim Depression are all distributed in the northern margin of Maigaiti slope, whereas the secondary gas reservoirs are all distributed in the south of Maigaiti slope.

The regularity of the oil and gas reservoirs distribution indicates that there are large-scale lateral migrations of hydrocarbons in the Southwest Tarim Depression. At present, the transport layer of the lateral migration of the oil and gas is poorly understood. Hydrocarbon explorations showed that the Ordovician-Carboniferous reservoirs in the Southwest Tarim Depression are distributed only in the fault zones. Therefore, the possibility of lateral hydrocarbon migration in the Ordovician-Carboniferous could be excluded. The lateral migration of oil and gas in the Southwest Tarim Depression most likely occurs in the Cambrian sub-salt strata.

The $\in_{1y}$ source rocks in the Southwest Tarim Depression have great hydrocarbon generation potential, which has been proved by the Ordovician-Carboniferous oil and gas reservoirs. The drilled wells in Bachu uplift indicate that the $\in_{1x}$ dolomite reservoirs are well developed in the Southwest Tarim Depression, favoring the sub-salt primary oil and gas reservoirs formation. Moreover, a regional gypsum-salt cap rock developed in the Southwest Tarim Depression, the tectonic deformation of which was relatively weak, favoring the preservation of the sub-salt primary oil and gas reservoirs. Therefore, it is reasonable to believe that the Cambrian sub-salt oil and gas in this area may be enriched more than the Cambrian post-salt oil and gas. Due to the existence of the $\in_{2a}$ thick salt strata in the Southwest Tarim Depression, the subsalt image in the seismic section is not clear. The degree of exploration of the Cambrian subsalt in the Southwest Tarim Depression has, therefore, been very limited. With the improvement of technology, the Cambrian subsalt strata will be an important exploration target in this area.

Conclusions

The Cambrian and Ordovician paleo-uplifts in the Southwest Tarim Depression had experienced multistage migration adjustment. The evolution of the Cambrian and Ordovician paleo-uplifts can be divided into four stages: (1) formation stage of the paleo-uplift in the Southwest Tarim Depression, (2) steady subsidence stage of paleo-uplift in the eastern segment of Southwest Tarim Depression, (3) migration and adjustment stage of paleo-uplift in the western segment of Southwest Tarim Depression, and (4) Strong subsidence and extinction stage of paleo-uplifts in the Southwest Tarim Depression.

The Cambrian and Ordovician strata in the Southwest Tarim Depression experienced a seesaw-like structural reconstruction process, from an early north-dipping slope into a late south-dipping slope. Moreover, the structural top of the western paleo-uplift moved northward before that of the eastern paleo-uplift. During the structural reconstruction process, a pivot zone located at the position of the current Maigaiti Slope was favorable for hydrocarbon accumulation and preservation.

The fault zones in the eastern and western paleo-uplifts of the Maigaiti slope that finalized during the Late Hercynian Period were favorable for the preservation of paleo-oil reservoirs, whereas the fault zones in the northern margin of the Maigaiti slope were favorable for the accumulation of later gas reservoirs.

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