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Deformation characteristics and exploration potential of the West Kunlun foreland fold-and-thrust belt

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Abstract:
The West Kunlun foreland is dominated by segmented fold-and-thrust belts with significant potential for hydrocarbon exploration, while the extent of exploration in this area has been relatively limited. In this paper, by conducting complex structural interpretation, the geometric and kinematic characteristics, as well as the variations in the segmented fold-and-thrust belts within this region are revealed. The West Kunlun foreland fold-and-thrust belts are divided into three structural segments, which exhibit distinct structural styles. The Pusha-Kedong segment in the east is characterized by large-scale northward propagation, with high-angle basement-involved faults in the root belt and thin-skinned thrusts in the front belt. Additionally, three-row anticlines developed in the middle to the upper structural layers. The Kashi-Yecheng segment, located in the middle, is characterized by strike-slip faults and basement-involved structural wedges transitioning to detachment structures. Within this segment, the Sugaite structure in the mountain front is a wedge structure composed of basement-involved faults and an upper back-thrust fault. Meanwhile, the Yingjisha structure in the thrust front consists of a fold in the lower part and a back-thrust system above it. The lower fold is controlled by the Cambrian detachment thrust, which terminates upward in the Paleogene, while the back-thrust faults truncate upper structural layers and terminate downwards in the Miocene strata. The Wupoer segment in the northwest is controlled by the Main Pamir Thrust and the Front Pamir Thrust, which are low angular forward thrust faults with an arc distribution. A piggyback basin has developed in the root belt and upper structural layer since the Pliocene. Based on the deformation characteristics and the accumulation of oil-gas reservoirs discovered so far, two types of oil and gas-rich thrust belts with different hydrocarbon exploration fields in the West Kunlun foreland are described.

1. Introduction

The continuous collision and convergence between the Indian and Eurasian plates in the Cenozoic has reactivated the Kunlun Mountain, Tianshan Mountain, and other Paleozoic orogenic belts around the Tarim Plate (Molnar and Tapponnier, 1975; Tapponnier et al., 1986). The strong uplift of the Miocene West Kunlun orogenic belt and the northward propagation of the Pamir salient resulted in the rapid flexural subsidence of the southwestern Tarim Basin (Cowgill, 2001; Dong et al., 2018). The West Kunlun foreland fold-and-thrust belt formed under the influence of north-south compression and the strong northward thrusting of the Pamir salient (Burtman, 2000). As the front structural belt of the plate convergence boundary/orogenic belt, the fold-and-thrust belt experienced lateral tectonic compression, and thus shows the thin-skinned tectonic style controlled by a regional detachment layer. This layer often develops a series of structural deformation belts with a similar geometry (Jia et al., 2022a). Some spatial geometric differences exist in the tectonic evolution

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of the West Kunlun fold-and-thrust belt (Cheng et al., 2017). Previous studies have discussed the boundary fault properties (Cowgill, 2001), the pre-existing structure (Wang et al., 2016), the distribution of the weak layer (Laborde et al., 2019; Wang et al., 2020), the differential subsidence of the basement (Tang et al., 2007), and the mechanism of deep collision (Gao et al., 2000). Researchers pointed out that the style of different structural belts in the thrust belt is determined by vertical stratification, dip zoning, and lateral segmentation (Jia et al., 2022b), while obvious differences were observed in their geological structure (Laborde et al., 2019).

From northwest to southeast, the West Kunlun fold-and-thrust belt can be divided into Wupoer thrust belt, Kashi-Yecheng strike-slip and thrust belt, and Fusha-Kedong thrust belt. Wu et al. (2021a) analyzed the style of the Kedong structure from vertical deep and shallow levels and established that the overall structure was characterized by "basement-involved at the rear margin and thin-skinned at the front cover". Wu et al. (2014) pointed out that the differences in tectonic denudation, sedimentation and basement subsidence effect on structural deformation resulted in the Wupoer structural belt being conducive to the formation of a piggyback basin, and the Kekeya-Kedong structural belt being conducive to the formation of passive roof duplex structures. Chen et al. (2017) discussed the role of boundary fault properties, weak beds and paleostructures on the segmented deformation of the thrust belt, and divided the thrust belt into different structural segments based on the deformation characteristics and properties of the above belts.

The segmentation of the West Kunlun piedmont fold-and-thrust belt is closely related to the northward propagation of the Pamir salient, and the study of structural segmentation is of great significance for revealing the far-field effects of plate collision and intracontinental orogeny (Wang et al., 2016). The West Kunlun foreland fold-thrust belt is located at the southwestern margin of the Tarim Basin and is a product of the collision between the Eurasian and Indian plates. This belt features multiple major thrust faults and folds, with strong tectonic deformation. In recent years, scholars have conducted extensive research on this belt and discovered its obvious tectonic segmentation. Each tectonic segment exhibits different structural styles and deformation characteristics. For example, the Upal segment is dominated by thrusting, forming high-angle thrust faults and anticlines, while the Suget segment is dominated by strike-slip thrusting, developing compressional folds and fault-bend folds.

Given its geological history, the West Kunlun fold-and-thrust belt has great potential for oil and gas exploration and has long been a key area in the study of basin-mountain coupled tectonic deformation and oil and gas exploration. Two major oil and gas producing areas, namely, Kekeya and Akemomu, have been discovered so far in this belt (Wang et al., 2020). Research on the structural deformation style and its deformation rule of the fold-and-thrust belt can have a significant guiding role on oil and gas exploration. Previous studies have enriched our understanding of the tectonic genesis and evolution process in this area (Chen et al., 2022). However, thorough explanations are lacking, especially of the deep structural problems that restrict the regional deformation process and mechanism, which seriously affect the oil and gas accumulation process analysis.

In this paper, focusing on the fold-and-thrust belt of the West Kunlun Mountains, the commonness and difference in the deformation characteristics of different structural parts and their variation rules are subjected to a detailed geometry analysis of the Mesozoic-Cenozoic tectonic deformation. Taking the current research progress as a basis, the control factors of the segmentation of structural deformation and the future direction of oil and gas exploration in this area are revealed.

2. Geological setting

The Southwestern Depression is situated in the southwest of the Tarim Basin. It shares its border with the western part of the South Tianshan foreland fold-and-thrust belt and the Bachu Uplift in the north, the West Kunlun foreland fold-and-thrust belt in the southwest, and the Tanggu Depression in the east. It is a rejuvenation foreland basin formed by Cenozoic compression on the basis of the Mesozoic collision orogenic belt. The Southwestern Depression has six secondary tectonic units: South Tianshan fold-and-thrust belt, Kashi Depression, West Kunlun fold-and-thrust belt, Yecheng depression, Hotan Depression, and Maigaiti slope (Fig. 1). The West Kunlun fold-and-thrust belt is located at the northern foot of the West Kunlun Mountains and forms part of the arc tectonic front on the eastern margin of the Pamir salient. The West Kunlun orogenic belt exhibits a generally reverse "S" = shaped distribution, which can be divided into Tiklik fault and Pamir front fault. The Pamir front fault can be further divided into two segments: Kashi-Yecheng strike-slip fault and main Pamir fault.

The Tarim Plate and its peripherals have been affected by the opening, subduction and closing of the Paleo-Asian and Tethys Ocean basins, as well as the collision and orogeny between micro-blocks since the Neoproterozoic (He et al., 2019). During the Mesoproterozoic and Early Paleozoic periods, the Tarim Plate and the Qiangtang-Yangtze Plate were separated. The southern margin of the Tarim Plate is situated at the present Kangxiwa fault in the West Kunlun Mountains. The entire area north of the Kangxiwa fault is in a tectonic environment of continental margin uplift, and almost all of the southwest depressions in this period are missing Cambrian to Silurian deposits. With the subduction of the Qiangtang-Yangtze Plate to the north in the late Paleozoic, the southern margin of the Tarim Plate entered the stage of active continental margin development. At this time, two large marginal sea basins were formed north of the Kangxiwa fault, and a large area of Devonian-Permian system was deposited. The tectonic evolution of the southwest Triassic depression has since shifted to the intracontinental stage, and the southwest part of the Tarim block is influenced by the compressional tectonic environment, which leads to the overall uplift and the absence of the Triassic system.

At the end of the Triassic, the Qiangtang-Yangtze Plate and the Tarim Plate coalesced entirely along the Kangxiwa fault. The Paleo-Tethys Ocean subducted and began continental

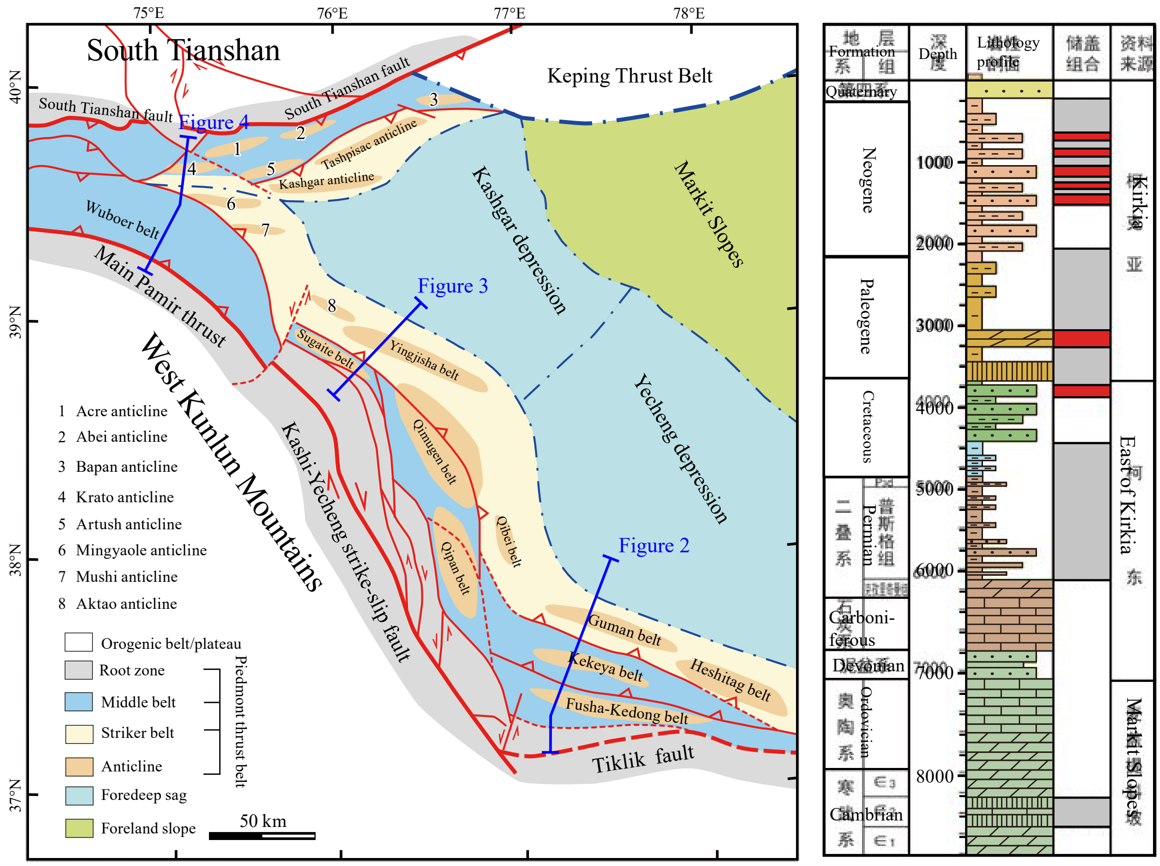

Fig. 1. Location, structural units and stratigraphic histogram of Southwest Depression in the Tarim Basin.

deposition (Cao et al., 2015). At this time, the embryonic foreland thrust belt of the Hercynian-Indosinian period in the southwest of Tarim began to form. From the Jurassic to the Paleogene, a back-arc extensional fault depression developed in the West Kunlun area based on the foreland thrust belt at the end of the Triassic. A set of coal-measure strata with a large distribution area were deposited during this period. From the Late Cretaceous to the Paleogene, the West Kunlun area underwent a transition from fault depression to extensional depression. This change was influenced by the transgression of Neo-Tethys, leading to the formation of a set of fine clastic rocks of marine-terrestrial transitional facies-carbon salt rock (Wu et al., 2021b).

The subduction of the Indian plate beneath the Eurasian plate in the Miocene resulted in a strong northward thrust expansion of the West Kunlun-Pamir arc orogenic belt (Cowgill et al., 2003; Chen et al., 2022). The Sugaite area, located in the fold-thrust belt of the Kunlun Mountains, underwent strong compression, leading to the development of several high-angle basement-involved faults in its southwest part, which resulted in the formation of Paleozoic-Mesozoic nappes. The Kedong area, located in the basin-mountain transition zone, began to undergo flexural structural deformation due to the far-field effect of the collision between the Indian and Eurasian plates. However, this deformation was less intensive. During the Pliocene-Holocene, the Pamir salient propagated further northward, leading to the rapid uplift of the Kunlun Mountains. The fault at the northern margin of the Pamir began to undergo strong thrusting and formed a large-scale fold-and-thrust belt (Cheng et al., 2016). The Permian strata in the Kedong area thrusts north along the high-angle thrust fault and overlaps the Mesozoic and Cenozoic strata to the north. This induces the footwall to form the Paleogene fault-propagating fold structure style, which essentially represents the current structural style in the Kedong area. During the initial period, the foreland basin of the West Kunlun Mountains deposited massive, thick molasse sediments of the Atushi Formation.

3. Stratigraphic development and distribution

The Early Paleozoic witnessed large-scale transgression that resulted in the extensive deposition of the Lower Paleozoic, Cambrian-Ordovician platform facies carbonate rocks, and Silurian clastic rocks in the Southwest Depression. In general, the Lower Paleozoic has limited distribution on the surface due to early multi-stage deformation. However, the Upper Paleozoic, which is dominated by marine sediments, is relatively complete in the West Kunlun Orogenic Belt. It is mainly comprised of neritic limestone and littoral-lacustrine sand-mudstone (Li et al., 1996). The thickness of the Upper Paleozoic in the West Kunlun orogenic belt is significantly greater than that in the interior of the depression, indicating that the southwestern Tarim region is a geological unit separating the north and south marine sedimentary systems.

The Middle Cambrian gypsum-salt rock, with a thickness of about 500 meters, developed in the depression during this period, which is an important structural detachment layer in the region. The Devonian system is primarily exposed in the form of fault blocks in the southwestern part of Tarim. It consists of littoral-neritic deposits and its lithology is mainly dark red and gray-green sandstone. The reverse fault pushes the Devonian to the Neogene system and is baked by the magmatic rock hydrothermal fluid, which is mainly interbedded with green gray and gray light metamorphic layered sandstone and siltstone of various thicknesses.

The Carboniferous system develops interbedded deposits of limestone and mudstone in shallow marine shelf facies, which is an important stratum for source rock development in the region. Carboniferous source rocks are distributed in the southwest depression, containing mainly dark mudstone, with an average thickness of 100-200 m. The Carboniferous Hantiereke Formation consists of interbedded limestone and mudstone, which serves as a source rock in the Kushanhe section. This formation has a thickness of 525 m and exhibits a total organic carbon (TOC) content of 0.38%-5.99%, with an average of 1.15%. The oil generation potential here is 0.02-0.62 mg/g, with an average value of 0.10 mg/g (taken from well data in the southwest Tarim Basin). These characteristics classify the Carboniferous Hantiereke Formation as a set of medium-good source rocks.

The Permian system consists of shallow marine platform-margin facies characterized by dark gray biogenic limestone deposits. In this area, the Qipan Formation and the upper part of the Pusige Formation serve as the primary sources of rock development. These formations exhibit an average thickness of 50-500 m, with thicker distribution in the west and thinner distribution in the east. The Qipan Formation is dominated by shallow marine shelf facies and is mainly distributed in the western Yecheng Depression to the Qibei area. The thickness of this formation decreases from west to east. The average thickness of source rocks here exceeds 100 m, with an average TOC content of 1.06%. On the other hand, the upper part of the Pusige Formation is dominated by lacustrine deposits, mainly distributed from the eastern part of the Yecheng Depression to the Kedong area. The average thickness of the source rocks exceeds 200 m, with an average TOC content of 0.97%. These characteristics classify it as a medium-preferred source rock. It is worth noting that due to the strong influence of thermal evolution, the Carboniferous-Permian source rocks have reached a late stage of high maturity, thus they primarily generate gas.

The Mesozoic is dominated by Jurassic and Cretaceous deposits, mainly distributed at the edge of the orogenic belt. These deposits overlap and thin into the basin. However, in the southwest of the Tarim Basin, the Triassic deposits are generally absent. The Jurassic era is characterized by a series of lacustrine-swamp facies deposits. The lithology of this era primarily consists of gray and dark gray mudstone and carbonaceous mudstone interbedded with coal seams (Lu et al., 2020).

Influenced by the depositional environment, the distribution of Jurassic source rocks is sporadic in the southwestern Tarim piedmont. In the northern part of the Kashi Depression, dark lacustrine mudstone deposits are present that serve as medium-good source rocks. Toward Yecheng, the depositional environment gradually transitions to fluvial facies and the organic matter type diminishes. The source rocks of the Jurassic Yangye Formation and Kangsu Formation in the Kushanhe section have a TOC content of 0.36%-11.89%, with an average of 2.0%. Their hydrocarbon generation potential is 0.06-11.13 mg/g, with an average value of 0.83 mg/g. These formations are in the mature-high mature stage, mainly exhibiting oil generation (include references).

During the Cretaceous period, the front of West Kunlun Mountains was situated in a depression basin and the Cretaceous deposits overlapped with the paleo-uplift to the north. The Lower Cretaceous era saw the development of braided river (fan) delta-shore shallow lacustrine deposits, which include of brown/red sandy mudstone and conglomerate-dominated strata. These deposits form an important reservoir development stratum in the region. The Lower Cretaceous Kizilsu Group in the Fusha-Kedong area is characterized by braided river delta-shallow lake facies deposits. According to data from Well Keshen 101, the reservoirs consist of brown pebble-bearing fine sandstone, fine sandstone and siltstone, and the porosity is 5%-15%. The thickness is stable in the east-west direction, gradually decreasing northward, ranging between 200-600 m and covering an area of approximately 4,500 km^2. In the Sugaite area, the thickness varies greatly, thinning and pinching out from east to south. The maximum thickness is 200-1,000 m, the area is about 3,100 km^2 and the porosity is 3%-20%. The Wupoer area is characterized by fan delta glutenite, which dominates the region and has a stable thickness along the front of Kunlun Mountains. The deposits thin and pinch out to the north, reach a thickness of 400-1,200 m, an area of about 1,800 km^2, and a porosity of 3%-10%. The reservoirs of the Kukebai Formation primarily consist of subtidal tidal channels, sand flat fine sandstone, and siltstone deposits. The sandstone reservoir of Well Kedong 5 features a thickness of 74.5 m and a porosity of 7.4%-16%.

The Cenozoic strata in the Southwest Depression are well developed and relatively thick. During the Paleogene era, gulf-lagoon facies clastic rock, limestone and gypsum mudstone were deposited, consistent with those of the Upper Cretaceous (Chen et al., 2017). The gypsum mud deposited in the closed bay and lagoon environment of the Aertashi Formation at the bottom is stable in the lateral distribution, reaching a thickness of 100-200 m. It is not only a high-quality regional caprock but also an important upper detachment layer, providing a favorable combination of storage and cover. The Paleogene Karatar Formation tidal flat cloud limestone reservoir and the overlying Wulagen Formation and Bashibulake Formation mudstone caprocks constitute the second reservoir-caprock combination in the area, which was the first pay zone in the Kekeya condensate gas field. According to data from Well Kedong 5, the Karatar Formation reservoir is 71.5 m thick and has an average porosity of 7.86%.

The Ulagen Formation mudstone caprock has a continuous thickness of 22.5 m, comprising a single thicker layer that is laterally widely distributed. The Miocene system is a set of widely distributed braided river delta-shallow lacustrine sand-shale deposits. The Miocene Keziluoyi Formation, Anju'an Formation sandstone, and overlying Pakabulake Formation mudstone are also favorable reservoir-caprock assemblages in the area. The Keziluoyi Formation and Anju'an Formation comprise a set of braided river delta facies deposits in an oxidative environment. Their lithology is mainly sandy and conglomerate, and the thickness in the area generally decreases from northwest to southeast. The reservoirs here are relatively thick and laterally widely distributed. The sandstone reservoirs of the Kizloyi Formation and Anju'an Formation at Well Su 2 are 317 m thick and have an average porosity of 3.50%. The Pliocene-Pleistocene (Atushi and Xiyu Formation) is a set of alluvial fan delta deposits. The lithology of the Pliocene Atushi Formation is characterized by thick layered variegated fine conglomerate and gray glutenite. The thick layered gravel represents a large set of piedmont alluvial fan deposits. In contrast, the Xiyu Formation consists of extremely thick layered conglomerate. The overall thickness in the area shows a trend of thinning from west to east, with significant variations.

The two regional detachment layers divide the southwest Tarim strata into three structural layers from bottom to top: The lower structural layer is composed of the deep crystalline basement and the Sinian-Lower Cambrian, which is located below the Cambrian detachment layer; the middle structural layer is located between two detachment layers and includes the Paleozoic and Mesozoic above the Middle Cambrian detachment layer; and the upper structural layer is located above the detachment layer of the mudstone and the evaporate of the Paleogene (Wang et al., 2013).

4. Structural deformation characteristics

The structural deformation of the West Kunlun fold-and-thrust belt is dominated by thrust, which is a superposition of multi-stage structural deformation. The Cenozoic structural deformation of thrust zones is significantly influenced by several factors, including the distribution of regional detachment layers, the nature of boundary faults, synsedimentation, and paleo-uplift. The Cambrian salt is absent on one side of the orogenic belt but is developed on the other side of the basin, except in the piedmont zone of the Sugaite-Yingjisha area and the Pishan-Hotan area (Xie et al., 2012). During the Cenozoic era, synsedimentation could prevent deep faults from reaching the surface and cause the deformation front to extend to the foreland over a long distance. The paleo-uplift in the early stage of the thrust zone played an important role in controlling the tectonic deformation in the later stage. The position of the paleo-uplift under the detachment layer is the favorable position for the development of the forward breakthrough fault. The nature of boundary faults and the development of strike-slip fault zones led to significant differences in tectonic evolution among the areas. According to the deformation characteristics of the thrust belt in the front of West Kunlun Mountains, the thrust belt can be divided into three structural segments: Wupoer structural belt (west segment), Kashi-Yecheng structural belt (middle segment), and Fusha-Kedong structural belt (east segment). Based on the structural characteristics of the thrust zone, the area can be divided into three zones: The root zone adjacent to the boundary fault of the orogenic belt, the middle zone with low angle thrust, and the front zone with less thrust.

4.1 Fusha-Kedong structural belt

The Fusha-Kedong structural belt is located in the eastern segment of the West Kunlun foreland fold-thrust belt. The structural strike is nearly east-west and perpendicular to the regional stress direction. The main feature of this belt is the three-row anticline structure of Pusha-Kedong, Kekeya, and Guman-Heshitag (Fig. 1). On the eastern segment, the belt generally shows a basement-involved thick-skinned structure, caused by high-angle thrust faults close to the piedmont and a thin-skinned detachment structure in the interior of the basin (Fig. 2). The root zone is formed by the Tiklik thrust fault system of the high-angle inclined orogenic belt, which is adjacent to the northern margin of the West Kunlun orogenic belt. It is composed of two main faults and multiple secondary faults. Thrust napping caused large-scale uplift of the basement, exposing the Upper Paleozoic in the hanging wall. The trend of the anticline transitions from nearly east-west in the east and NWW-SEE in the west. With the extension of the thrust belt to the foreland, 3-4 rows of low-angle thrust faults developed in the middle structural layer, breaking into the bottom of the Paleogene system. The bottom subsequently converged to the Middle Cambrian detachment layer and locally developed small-scale back-thrust faults. The overlying Cenozoic was passively uplifted to form the Kekeya anticline, and the core of the anticline exposed Miocene and Pliocene strata.

The Pliocene Atushi Formation on the north wing of the anticline exhibits the characteristics of growth strata. The south-dipping thrust fault at the front end of the Kekeya anticline constitutes an imbricated fan; small fault propagation folds occurred in the Cenozoic strata, forming the Guman anticline. At the same time, the extremely thick Neogene synsedimentary strata facilitated the Paleogene gypsum mudstone to produce a good detachment effect, which inhibited the breakthrough of deep faults to the surface. The deformation front indicates that the thin-skinned detachment structure extended to the landward direction.

4.2 Kashi-Yecheng structural belt

The Kashi-Yecheng structural belt is located in the middle segment of the West Kunlun foreland fold-and-thrust belt on the eastern margin of the Pamirs. It is generally subject to oblique compression. From south to north, the segment can be further divided into 5 structural belts: Qipan, Qibei, Qimgen, Yingjisha, and Sugaite (Fig. 1). The structural deformation in the middle segment is mainly concentrated in the middle and lower structural layers. In general, the hinterland side exhibits a stacking structure, while the foreland side displays a thin-skinned imbricated fan structure (Fig. 3). Due to oblique compression, the upward thrusting amplitude of the boundary thrust fault in the root zone is smaller than that of the eastern

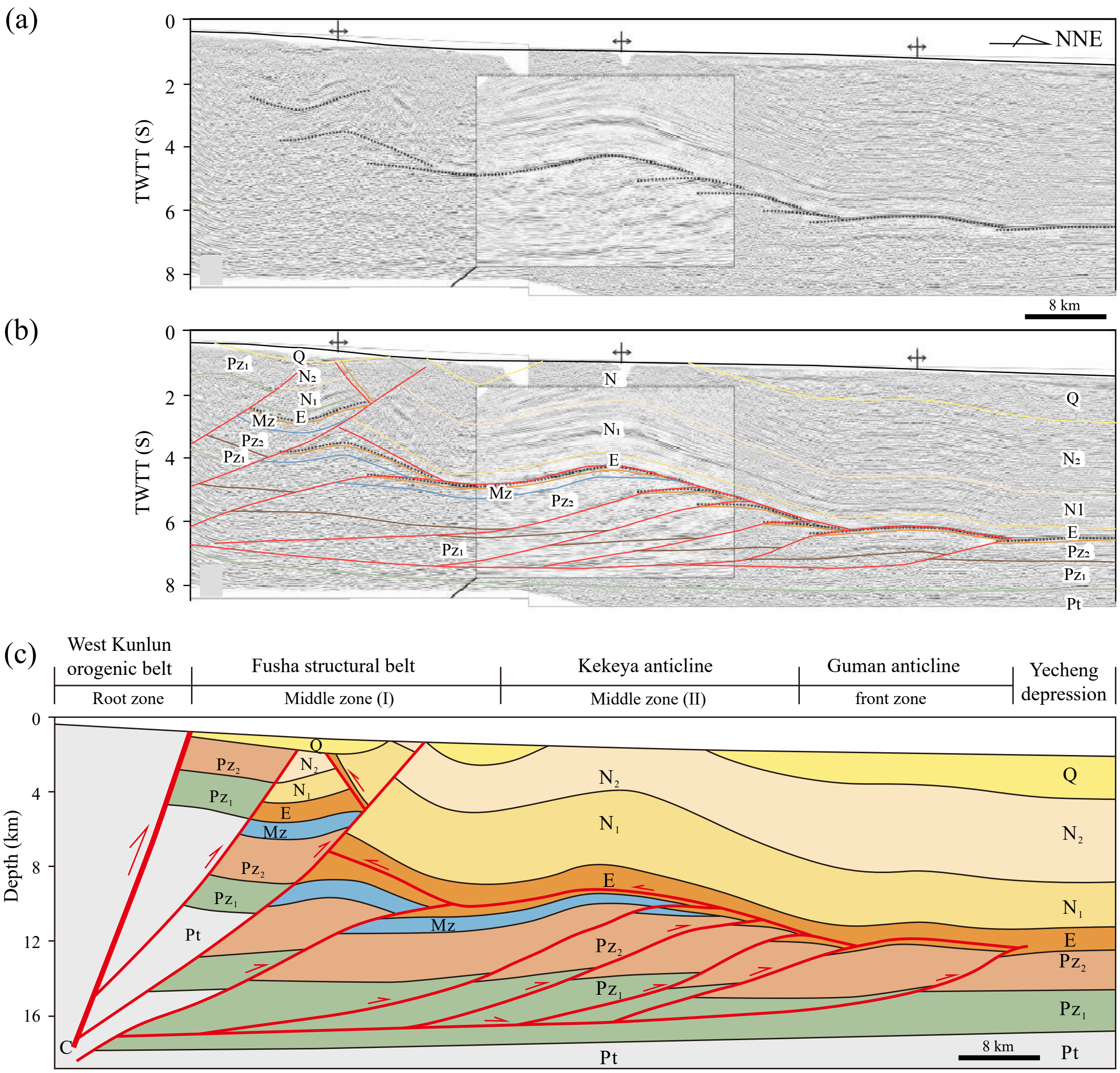

Fig. 2. Structural profile in the eastern segment of fold-thrust belts in the front of Western Kunlun. (a) Seismic profiles, (b) seismic interpretation and (c) structural pattern.

segment and exhibits a dextral strike-slip property.

The Paleozoic system is exposed on the hanging wall of the boundary fault at the southernmost part of the profile. It is covered by the Quaternary in the foreland direction and partially exposed by the Neogene. Well Su 2 revealed a 4,083 m-thick Devonian thrust nappe in the shallow part of the Sugaite structure. The overlying anticline formed by the passive uplift of the upper structural layer presents two forms: Monocline and interval anticline. It covers a width of about 10 km of the Cenozoic strata. In the deep part of the Sugaite structural belt in the middle zone, several Cenozoic thrusts developed that were involved in deformation, and these thrusts were superimposed on each other to form a stacking structure. The deep layer of the Yingjisha structural belt in the frontier zone is a fault transition fold controlled by the Cambrian detachment layer, and the thrust fault terminates upward in the Paleogene gypsum-mudstone detachment layer. The upper structural layer was cut off by late back-thrust faults, which terminated in the Miocene strata.

The Yingjisha anticline formed as a result of the above events, which exhibits larger shallow structural amplitudes and smaller deep structural amplitudes. The Cambrian salt detachment layer, located at the base of the Kashi-Yecheng structural segment, is distributed close to the piedmont. In the lower structural layer, caprock detachment faults are prone to develop. The north-south belt is wide, while the middle belt is narrow. Under the combined influence of the Cambrian gypsum-salt layer detachment layer, Paleogene gypsum-mudstone detachment layer, and the syn-sedimentation of the upper structural layer, the compressive stress propagates extensively towards the foreland. Consequently, a thin-skinned imbricated fan structure develops in the frontal zone.

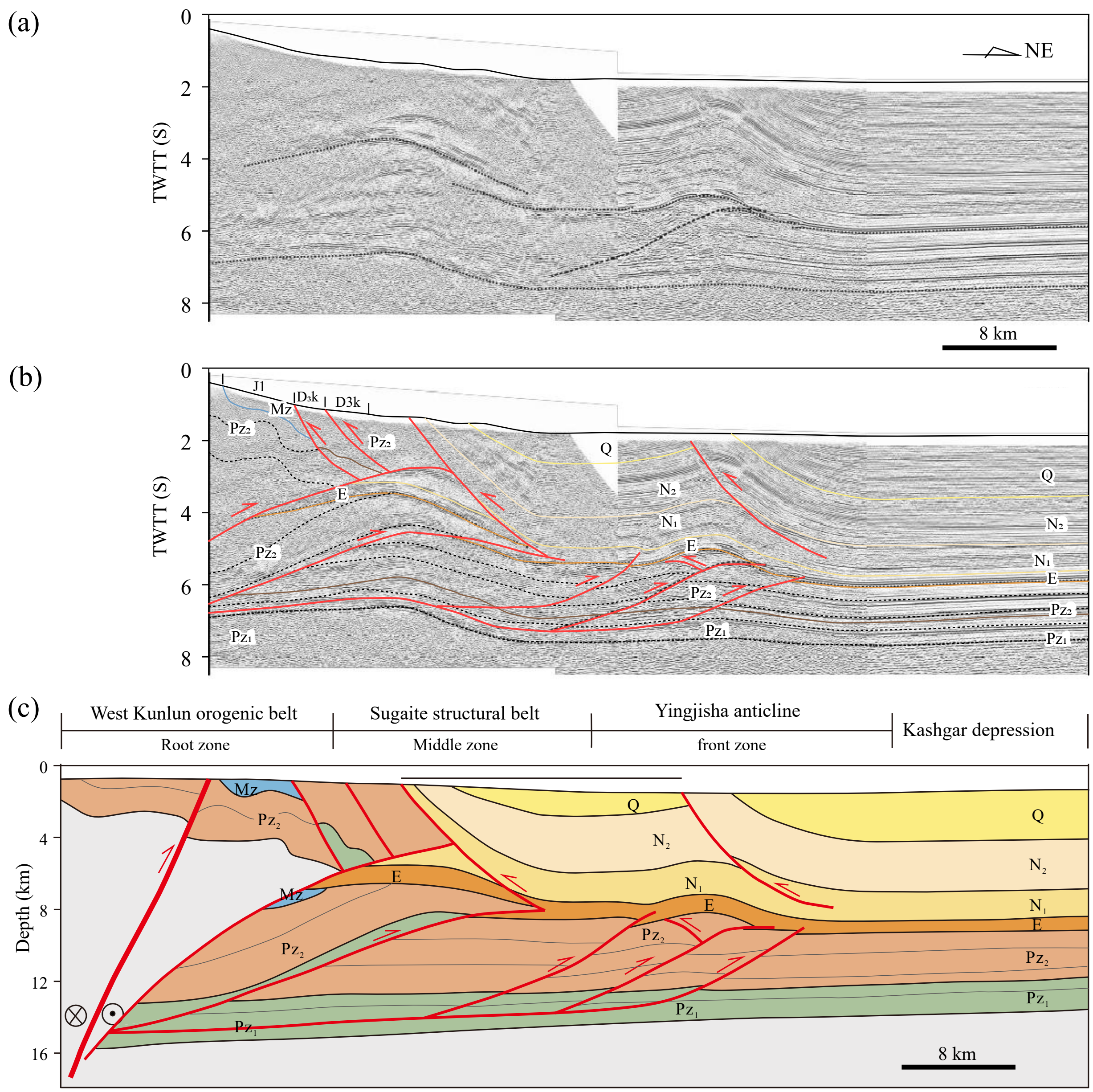

Fig. 3. Structural profile in the middle segment of fold-thrust belts in the front of Western Kunlun. (a) Seismic profiles, (b) seismic interpretation and (c) structural pattern.

4.3 Wupoer structural belt

The Wupoer structural belt is located in the northwest segment of the West Kunlun foreland fold-thrust belt front. It is bounded by the Kurgan dextral compression-shear fault in the east, distributed in an NW-SE arc on the plane, and represents the front edge of the main Pamir fault (Fig. 1). A significant characteristic of the Wupoer structural belt is that the structural deformation is primarily concentrated on the Wupoer fault and its hanging wall, with almost no major structural deformation on the footwall (Fig. 4). The root zone is characterized by the dominance of Pamir fault and its hanging wall. It exhibits a basement-involved structure in the front of Pamir Mountain, with the Upper Paleozoic thrusts occurring along the high-angle fault towards the Mesozoic-Cenozoic. The middle zone is controlled by the Wupoer fault, which is a basement-involved fault at depth. The shallow part of this fault converges upward along the Paleogene gypsum-mudstone detachment layer, eventually reaching the surface. On the hanging wall of the Wupoer Fault, two structural layers can be distinguished: Deep and shallow. The Paleogene detachment layer serves as the boundary between these layers. The deep structural layer exhibits several thrust-imbricated fault combinations, while different thrust slices give rise to fault transition folds or breakthrough structures. The lower structural layer develops fault transition folds mainly composed of Neogene strata. The upper part is clamped by the low-angle Wupoer overthrust fault and the root zone fault to form a camel-style basin. The front is mainly the blind thrust system of the footwall of the Wupoer fault. The upper structural layer develops the

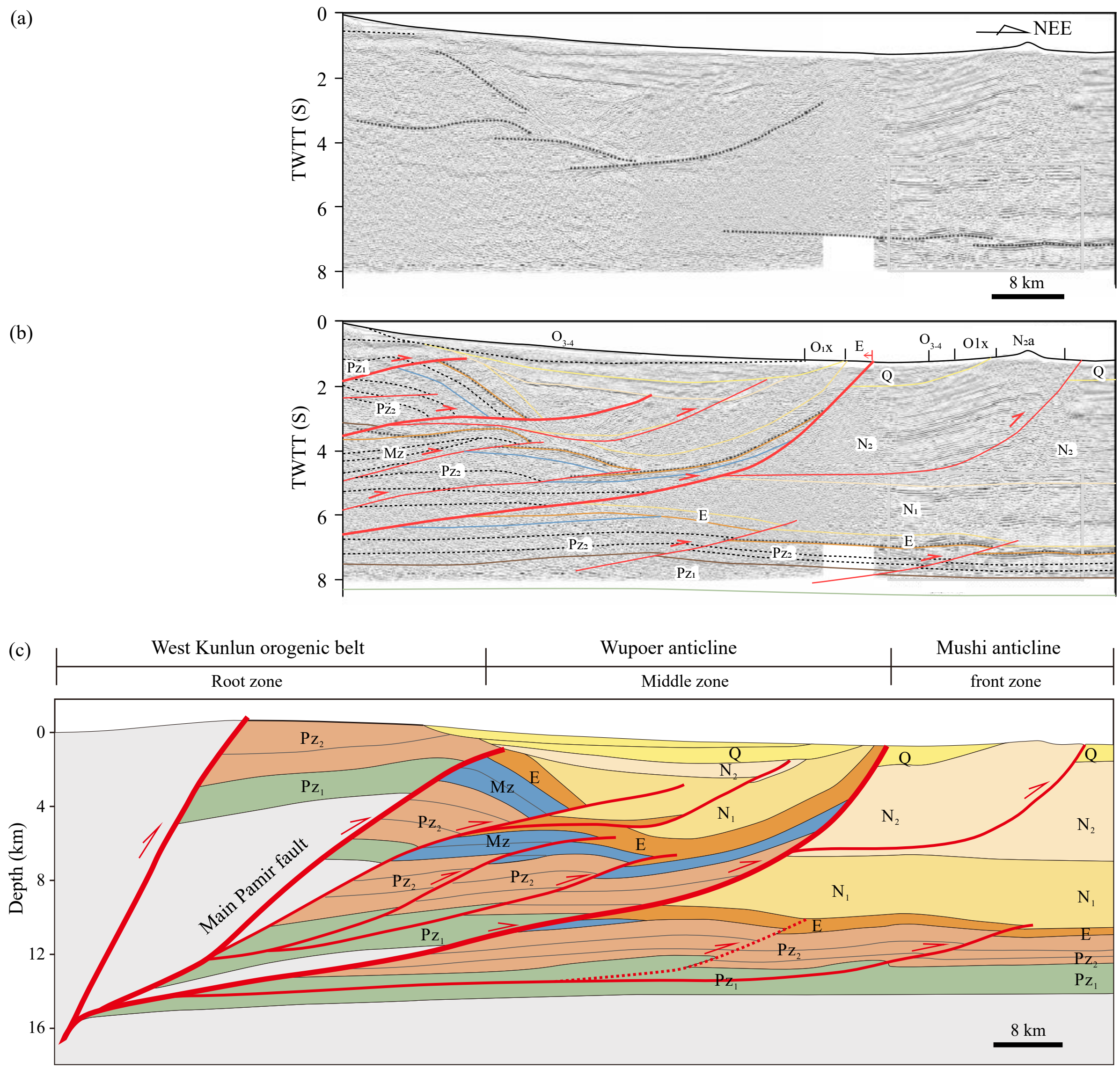

Fig. 4. Structural profile in the western segment of fold-thrust belts in the front of Western Kunlun. (a) Seismic profiles, (b) seismic interpretation and (c) structural pattern.

snake head anticline, which is controlled by Pliocene shovel faults. The middle and lower structural layers develop caprock detachment imbricated structures. The structural deformation of the Wupoer belt is mainly controlled by the gypsum-mudstone detachment layer at the bottom of the Paleogene, the pre-existing structures beneath the detachment layer, and synsedimentation.

5. Structural combination patterns

The West Kunlun foreland fold-thrust belt is subjected to compression or compressive shear, resulting in complex structural deformation and variable structural styles. Each structural segment exhibits deep and large basement faults, while the footwall features low-angle basement-involved faults that extend into the basin, gradually transitioning to a caprock detachment deformation. The detachment of each structural segment in the West Kunlun fold-thrust belt varies due to factors such as the uneven distribution of Cambrian gypsum-salt detachment layers in the piedmont, synsedimentation of the overlying Cenozoic, and differences in the nature of boundary faults. These variations give rise to distinct structural styles and combinations of features. According to the typical section features, six structural combination styles have been identified in the piedmont fault system: Basement-involved wedge structure, thin-skinned detachment imbricated structure, passive roof duplex structure, rabbit-ear structure, piggyback basin, and snake head anticline (Table 1).

Basement-involved imbricated structures have developed in the hanging wall of the West Kunlun fold-thrust belt. Due to the absence of Middle Cambrian in the orogenic belt (Wang et al., 2013), the piedmont thrust system in the southwestern Tarim Basin possesses the conditions to form high-angle basement-involved imbricate structures. The high-angle basement-involved faults, which appear to be inclined

Table 1. Structural style characteristics of fold-thrust belts in the front of Western Kunlun.

Structural style	Structure segmentation	Structural zoning	Structural layers	Feature of origin
Basement-involved wedge	Wupoer segment Sugaite segment Pusha-Kedong segment	Root zone-posterior margin of middle zone	Upper, middle and lower structural layers	The high-angle basement involvement fault is superimposed in the foreland direction and the fault converges to the boundary fault
Cap slip imbrication	Wupoer segment	Leading edge of middle band-forward band	Middle structural layers	The slip fault layers of more than two caps are superimposed and converge downward to slip delamination
Passive top plate type dual	Pusha-Kedong segment	Leading edge of middle band-forward band	Upper, middle structural layers	The deep thrust fault terminates in the Paleogene, and the roof fault and the upper structural layer are deformed into asymmetric Kekeya anticline and solid anticline
Rabbit-ear	Sugaite segment	Leading edge of middle band-forward band	Upper, middle structural layers	The deep thrust fault terminates in the Paleogene, the shallow thrust converges downward into the Anjuan Formation, and the upper structural layer is passively uplifted to form the Yingjisha anticline
Piggyback basin	Wupoer segment	Middle band	Upper structural layers	The Wupoer fault overthrust and the root zone fault forms the back bending basin, superimposed on the deep imbrication structure
Snake head	Wupoer segment	Leading edge band	Upper structural layers	The Wupoer fault forms the Sheephead structure with the shallow shovel fault at the front

to orogens, break through the surface and superimpose in the foreland direction. The thrust nappe causes large-scale uplift of the basement. The branch faults of the strike-slip fault develop in an imbricate shape. Wedge structures are formed when displacements from deep thrust faults are transmitted upward to shallow, oppositely dipping backthrust faults. The basement-involved wedge-shaped structure mostly develops from the footwall of the deep fault in the root zone to the rear edge of the middle zone, showing a series of basement-involved faults in the form of a backhoe. These faults develop upward and terminate in the upper detachment layer of the Paleogene system, while the shallow strata exhibit passive monoclinic structure (Fig. 5(a)).

For example, the Tiklik basement in the Fusha-Kedong structural belt is involved in the fault front, and 3-4 rows of basement-involved faults are developed in the foreland direction. The occurrence gradually slows down from deep to shallow. The deep thrust structure does not involve the deformation of the basement; however, when it is the detachment deformation at the bottom of the caprock, it exhibits characteristics of a duplex structure. Both the Fusha-Kedong belt and the Kashi-Yecheng belt have developed a duplex structure of middle and upper structural layers in the front belt. The low-angle thrust faults at the front edge of the middle zone slipped along the Middle Cambrian gypsum rock, and the deep thrust faults terminated upward in the Paleogene. With the increase in the displacement and the gravitational load generated by the synsedimentary strata, the propagation of deformation in the foreland direction is blocked, and the shallow structural deformation is more inclined to develop backthrust structures or passive roof faults in the hinterland direction. The roof faults of the Pusha-Kedong structural belt are developed in the Paleogene gypsum mudstone detachment.

The roof faults and upper structural layers are passively folded and deformed to develop asymmetrical Kekeya anticlines and Guman anticlines, establishing a passive roof duplex structure (Fig. 5(b)). The foreland direction of the Yingjisha anticline in the Kashi-Yecheng section is blocked by the synsedimentary strata to form a backthrust fault. The upper structural layer is cut off by the backthrust fault and converges downward to the Miocene Anju'an Formation to create a rabbit-ear structure (Fig. 5(c)). The shallow backthrust faults and deep faults of the rabbit ear structure did not merge, and the throw of the backthrust fault was less than the sum of the throws of the deep thrusts.

The piggyback basin and the snake head structure developed in the upper structural layer of the middle belt of the Wupoer structural belt, and the overthrust of the Wupoer fault and the main Pamir fault in the root zone formed the N_2-Q piggyback basin (Fig. 5(d)). The middle and lower structural layers of the thrust belt are thrust-imbricated structures composed of faults that converge upward to the Paleogene. The Mushi anticline zone the and Mingyaole anticline zone developed in the upper structural layer of the frontier belt of the Wupoer section, which are snake head structures controlled by two listric faults, superimposed on the deep caprock detachment-imbricated structure. In addition to the differences in structural combination patterns caused by detachment layers

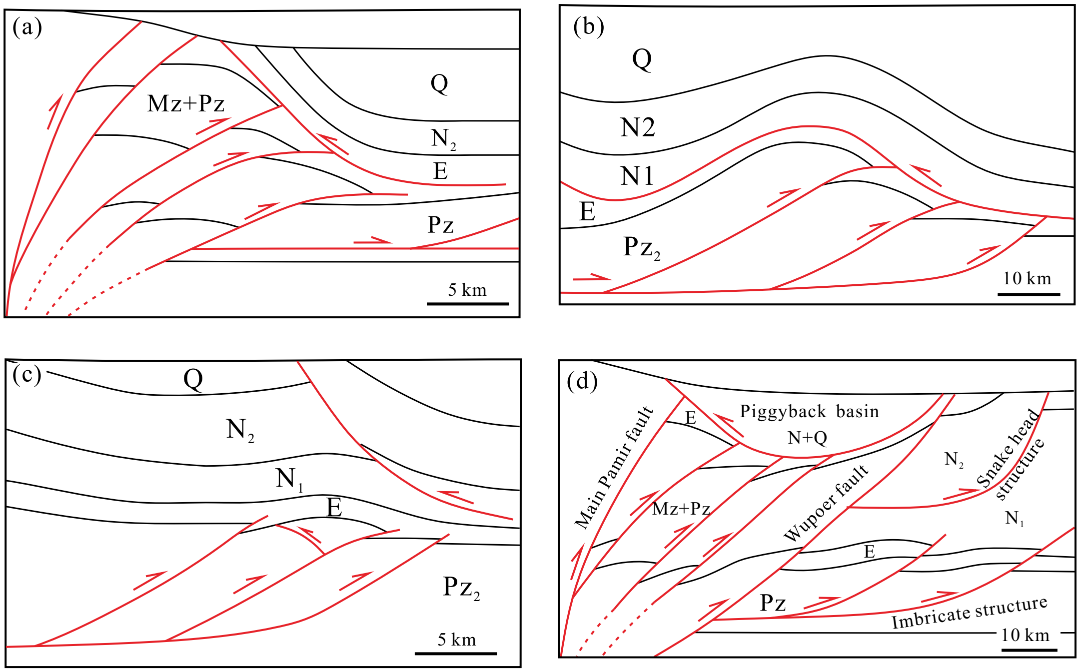

Fig. 5. Structural styles of the fold-thrust belts in the front of Western Kunlun. (a) passive monoclinic structure, (b) passive roof duplex structure, (c) rabbit-ear structure and (d) formation of the piggyback basin.

and synsedimentation, the distribution of frontal faults is also different due to the different boundary conditions of the individual structural segments.

6. Exploration potential

The western Kunlun piedmont thrust belt is a unilateral flexural subsidence caused by the uplift of the adjacent orogenic belt, featuring a significant Cenozoic syntectonic sedimentation thrust-type fold-thrust belt. Oil and gas exploration in this region began in the 1980s. To date, the Kekeya, Akemomu oil and gas fields, as well as the Kedong 1 condensate gas reservoir, have been discovered. The four evaluations of the Southwest Depression estimated the presence of 450 million tons of oil and 1.9 trillion square meters of natural gas. The degree of exploration has been relatively low, indicating that the West Kunlun Mountain Front still has great exploration potential (Huang et al., 2022).

The Carboniferous and Permian source rocks are widely developed in the front of West Kunlun Mountains. The thickness of Carboniferous source rocks ranges from 20 to 100 m, with the main body distributed in the Qipan structural belt to the Kedong structural belt. The medium-high abundance lacustrine source rocks of the Permian Pusige Formation are mainly located in the Kedong and Sugaite structural sections, with a thickness of up to 200 m. These two sets of source rocks in the western Kunlun Mountains are in the highly over-mature oil and gas generation stage and form the main source rocks in the region (Fig. 6). The analysis of discovered oil and gas fields (reservoirs) shows that the oil sources of the Kedong and Kekeya condensate gas fields are all from the lacustrine source rocks of the Permian Pusige Formation . The Kekeya oil and gas reservoir is located in the middle belt of the eastern segment of the thrust system. The structural-sedimentary and thermal evolution history indicates that the Kekeya structural belt underwent two stages of oil and gas charging in the Pliocene and Pleistocene. The Kedong anticline was formed in the Pliocene, and the Permian source rocks also reached the hydrocarbon generation peak in this period (Tian et al., 2022). The paleo-oil and gas reservoirs of Cretaceous and Paleogene strata were formed in the middle and late Pliocene.

The Permian source rocks reached a high degree of evolution in the Middle Pleistocene, and condensate gas infilled the paleo-reservoirs, leading to oil and gas adjustment. By the Late Pleistocene, gas charging and adjustment had resulted in oil and gas preservation in structurally stable areas. The hydrocarbon expulsion and tectonic activities of the source rocks in the piedmont thrust belt began in the early Miocene, and hydrocarbon accumulation was mainly affected by regional tectonic activities and the distribution of reservoir-cap assemblages.

Due to the influence of the original structure, sedimentary filling, and Cenozoic weak structural modification, the Pusha-Kedong and Sugaite structural belts are currently the main development areas of favorable reservoirs in the Lower Cretaceous. The basement faults developed in the middle belt fault system can effectively connect oil sources, and the regional unconformities commonly developed at the bottom of the Carboniferous and the top of the Permian also provide conditions for long-distance oil and gas migration. Therefore, the near-source thrust structure with large-scale reservoirs formed under the regional detachment layer (sedimentary cover) is a key area of oil and gas exploration in the fault system of the middle

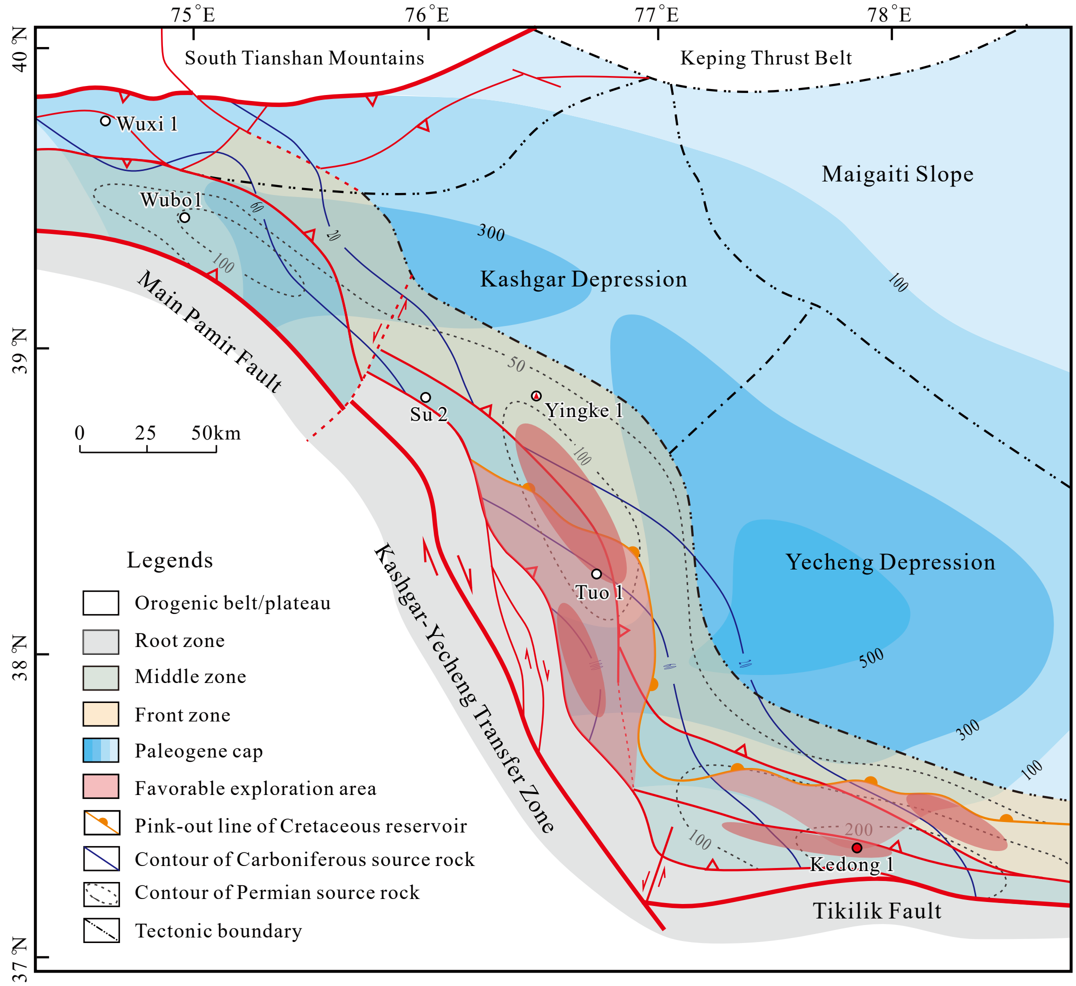

Fig. 6. Favorable exploration areas of the fold-thrust belts in the front of Western Kunlun. (1) The contour lines of Carboniferous-Permian hydrocarbon source rocks are based on the well data in the southwestern Tarim Basin. (2) The overlap line of the Cretaceous reservoir is the boundary of the sand body with greater than 5% porosity in the Kezilesu Group. (3) The thickness of sedimentary cover is based on the gypsum thickness of the Paleogene (Aertashi Formation). (4) The favorable exploration areas were determined by the comprehensive evaluation of favorable areas for Cretaceous sandstone reservoirs, the overlapping development of Carboniferous-Permian hydrocarbon source rocks, sedimentary cover thickness greater than 100 m, and structurally favorable areas.

zone. The front fault system is dominated by detachment structure deformation, with the Cretaceous reservoir being truncated. The favorable reservoir-cap assemblages in the area include the development of Albian carbonate reservoirs of the Kalatar Formation, the overlying mudstone caprock of the Ulagen Formation, as well as the Miocene sandstone and Pliocene mudstone. Separated by Paleogene gypsum mudstone, the development of oil source faults and the formation of effective traps are the key factors of oil and gas accumulation. In addition, the basement faults in the root zone can effectively connect the deep oil sources, and thrust structures with weaker activity in the footwall of the fault system are also worth exploring.

7. Conclusions

The West Kunlun foreland fold-and-thrust belt can be divided into three structural segments with significant structural differences:

1) The structural deformation of the Pusha-Kedong belt is dominated by thrusting. It transitions from a root zone with high-angle basement-involved faults to a middle zone with low-angle basement-involved thrust faults. The front zone exhibits a thin-skinned imbricated fan structure with a middle and upper three-row anticline structure.
2) The Kashi-Yecheng belt is characterized by strike-slip and thrust. The middle zone consists of deep basement-related thrust faults and shallow back-thrust faults, forming a duplex structure.
3) The Wupoer structural belt is controlled by the main

Pamir fault and its northern margin fault. It features arc-shaped low-angle forward thrust faults in the root zone. The low-angle overthrust fault and the root zone fault are clamped to form a camel-shaped basin.

In terms of formation mechanism, these segments in the West Kunlun fold-thrust belt exhibit distinct characteristics due to factors such as the uneven distribution of Cambrian gypsum-salt detachment layers in the piedmont, the overlying Cenozoic synsedimentary deformation, and the differences in the nature of boundary faults. In hydrocarbon exploration, the comprehensive analysis of accumulation conditions reveals the development of near-source thrust structures with large-scale reservoirs under the detachment layer in the fault system area of the Kedong Middle Zone. Among them, the carbonate rocks and the Miocene sandstone reservoir-cap assemblage constitute an important exploration zone in the front of the West Kunlun Mountains.

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Conflict of interest

The authors declare no competing interest.

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