Structural modeling and evolution of the piedmont zone in north margin of Qaidam Basin, northeastern Tibetan Plateau

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Abstract
The analysis and interpretation of the Dachaidan area, Qaidam Basin, is difficult, owing to the co-location of two groups of thrust faults (N–E faults and N–W faults) there and the area’s complicated structural deformation history. To address this problem, field geological investigation, seismic study, well logging, and drilling data were used to identify the key fault systems and their distribution patterns through the area. By integrating surface and subsurface structural features and seismic and non-seismic data, we carried out studies using structural modeling and analysis of the Dachaidan area. Study results identified two systems of thrust faults (N–W faults and W–E faults). We found that these faults could be categorized into three systems: a basin-margin thrust system, an intro-basin thrust system, and an intro-basin compression and strike-slip fault system. These systems showed different features in different areas and zones. We also constructed interpretation models of different deformation mechanisms in the basin and on basin margins. Three tectonic systems (compression, extension, and strike-slip) were identified, which were further divided into eight structural domains. We also established structure coexistence and distribution patterns. The overall structural character of the area was summarized as the northern and southern parts belonging to different zones, with the western and eastern parts belonging to different systems. By analyzing the SW–NE tectonic evolution sections, we defined the
back-propagation structural evolution sequences of thrust nappes (on the basin margin or in the basin) and back-thrust structures (in the basin) as well as their influence on the residual Mesozoic strata.

**Keywords**
Tectonic deformation, structure modeling, fault combination, Dachaidan area, Qaidam Basin

**Introduction**
The Qaidam Basin is an important petroleum-producing basin in Northwest China (Jun et al., 2020). The oil and gas exploration began in 1954, and 29 oil and gas fields have been discovered so far. Proved oil and gas geological reserves of $10.2 \times 10^8$ t, the current annual oil and gas equivalent reaches $800 \times 10^4$ t (Chen et al., 2020; Fu et al., 2016).

The Qaidam Basin is the largest continental sedimentary basin in the northeast Qinghai–Tibet Plateau. It is separated from the Southern Qilian Mountain by a thrust fault zone at its northern boundary, from the Tarim Basin by the Altyn Tagh strike-slip fault zone in the west, and from the Eastern Kunlun orogenic belt and West Qinling orogenic belt by the Eastern Kunlun fault and Elashan Mountain Fault in the southwest and southeast (Jian et al., 2013; Meyer et al., 1998; Yin et al., 2002). The tectonic deformation and evolution of the Qaidam Basin has been directly controlled by three major faults, and there is clear basin–mountain coupling. Basin sedimentation has preserved a complete record of the Qinghai–Tibet Plateau uplift and basin evolution, making this an ideal area in which to study both the Qinghai–Tibet Plateau uplift and the effects of basin–mountain coupling (Kapp, et al., 2003; Metivier, et al., 1998; Wen, et al., 2014; Xia, et al., 2001; Yin, et al., 2002; Zhu, et al., 2006). In recent years, many scholars, such as Jiang et al. (2008), Feng et al. (2011), and Fang et al. (2013), have conducted comprehensive investigations into the tectonic deformation and evolution of the Qaidam Basin and have characterized it as a basement-involved deformation dominated by compression under strike-slip regulation. Three stages in its evolution have been identified on the basis of analysis of the distribution of fault systems, the tectonic framework, and the characteristics of the deformation in the periods of structural activity. This existing analysis provides guidance for studies of the structure of the basin and its development. However, the complexity of the tectonic deformation at the north margin of the Qaidam Basin hinders the progress of oil-gas exploration in the region. There is an urgent need for a more detailed, robust tectonic model, a clarification of the process of structural evolution, and a better understanding of the factors controlling stratum development and distribution.

The Dachaidan area studied herein is located in the middle part of the northern margin of the Qaidam Basin, from the Yuka Depression at the base of Saishiteng Mountain in the west to the Hongshan Depression in the east, and is bounded by the Mahai–Dahonggou salient and Xitieshan Mountain in the south. The Dachaidan area features a Mesozoic hydrocarbon-bearing system based on a Middle-Lower Jurassic series of hydrocarbon source rock (Dang et al., 2003; Hu et al., 2001; Li et al., 2015; Wang et al., 2005; Wei et al., 2005). Hydrocarbon deposits have been discovered mainly in the west of the north margin of the Qaidam Basin (Chen et al., 2005; Li et al., 2002). In the Dachaidan area,
conversely, oil and gas exploration has been restricted as the greater complexity of the geological structure and tectonic deformation has hampered understanding of the basin–mountain coupling relationship, the structural characteristics, and the tectonic deformation of and controls on the distribution of the main Middle-Lower Jurassic hydrocarbon-generating beds. The Mesozoic–Cenozoic fault system, tectonic deformation, and structure are analyzed herein through an optimal use of regional seismic, gravitational, electrical, and borehole data, and other information. The influence of tectonic movement on the deformation and stratigraphic distribution in different periods was investigated through a structural evolution analysis.

**Type and distribution of the fault system**

*Fault system division*

The fault can be divided into the basin-margin thrust system, intra-basin thrust system, and intra-basin compression strike-slip fault system on the basis of the characteristics of the fault development and combined types of faulting (Table 1 and Figure 1).

**Basin-margin thrust fault system.** The basin-margin thrust fault system is part of the fault system at the southern margin of Qilian Mountain. In the study area, it is composed of Qaidam Mountain, Kuerleike Mountain (V.), the Hongshan syncline, and other scattered piedmont thrust fault zones toward the southeast, including the Qaidam and Hongshan Faults. The system is approximately 146 km in length, and its strike gradually transitions to NW and then to NWW from west to east. The western section of Qaidam Mountain features characteristics of low-angle thrusting, with the Proterozoic bedrock and Beishan Jurassic nappe outcrops over the Jurassic stratum, extending to a maximum distance of 6 km, forming a micro piggyback basin; the piedmont coal boreholes also demonstrate this pattern. The Eastern Dachaidan depression shows evidence of high-angle thrusting. The large Hongshan thrust nappe fault is particularly clear: Kuerleike Mountain and the Hongshan synclines are thrust nappes forming synclinal ridges (Fu et al., 2014; Mao et al., 2016; Wei et al., 2016).

**Intra-basin thrust system.** The intra-basin thrust system is part of the Sainan–Lvnan thrust fault system. It is composed of the Sainan and Lvnan Fault zones and strikes NW. The Sainan Fault divides the Gaxi and Yuka depressions and shows low-angle thrust nappe characteristics, with a nappe distance of 8–9 km. Lvnan Fault is in the south of the Lvlang piedmont and forms its boundary fault. The western part of the fault is intersected by the Maxian Fault at the Lvliang piedmont. It is approximately 90 km in length, strikes NW, and is inclined at 50°–80°. The western and eastern faults show thrust nappe characteristics, and the middle section is a high-angle thrust. The joint action of dextrorotation compression torsion at the northern margin of the Qaidam Basin and levorotation compression torsion on the Maxian Fault have led to dextrorotation compression torsion on the Lvnan Fault and to feather faults related to dextrorotation, forming the Dahonggou salient in the east, making an anti-S shape.

**Intra-basin compression strike-slip fault system.** The compression strike-slip fault system in the study area includes the Maxian and Lingjian Faults, of which the Maxian Fault is the most
Table 1. Parameters of key faults in the Dachaidan area.

| Fault system division | SN | Fault name          | Level | Strike    | Extending length | Fault nature           |
|-----------------------|----|---------------------|-------|-----------|------------------|-------------------------|
| Basin margin thrust   | 1  | Southern Qilian     | Level 1 | NW–WE    | 330              | Thrust fault            |
| fault system          | 11 | Qaidam              | Level 3 | NW–WE    | 48               | Thrust fault            |
|                       | 12 | Hongshan            | Level 3 | NW–WE    | 78               | Thrust fault            |
| Intro basin thrust    | 2  | Sainan              | Level 2 | NW       | 150              | Thrust fault            |
| system                | 3  | Lvnan               | Level 2 | NW       | 90               | Thrust fault            |
| Intro basin           | 4  | Xitieshan Mountain  | Level 2 | NW       | 41               | Thrust fault            |
| compression + strike   | 5  | Lingjian            | Level 3 | NW–NWW   | 139              | Thrust + laevorotation strike slip |
| slip fault system     | 6  | Maxian              | Level 3 | WE       | 65               | Thrust + laevorotation strike slip |
|                       | 7  | Xiaochaidan         | Level 3 | WE       | 44               | Thrust fault            |
|                       | 8  | Quanji              | Level 3 | NE       | 21               | Normal                  |
|                       | 9  | Lvbei               | Level 3 | NW       | 48               | Thrust fault            |
|                       | 10 | Xibei               | Level 3 | NW       | 26               | Thrust fault            |
The fault is a boundary fault between the Luxi sag and the Dahonggou bulge in Mahai. It starts from the north wing of the Nanbaxian structure in the west and extends to the front of the Lyliang Mountain in the west. It tends to SE, and the inclination angle is steep and slow, with an extension length of about 65 km. The layer J$_2$-N$_2$ is disconnected, and the maximum breaking distance is up to 3500 m, which has the characteristics of left-slide sliding compression. The west section of the Maxian fault is steep in section, with high angle thrusting, and the thrust amplitude is small; the east section is slow, the thrust and strike-slip distance are large, and the Sai Nan and Lunan faults are staggered; staggered distance 8 km.

The Maxian fault developed in the Yanshanian period, strongly active in the middle of the Himalayan, and shaped in the late Himalayan, controlling the formation and evolution of the Mabei bulge. In the late Yanshanian (late Cretaceous), the first stage of the Maxian fault was strongly active. The Mabei bulge on the upper plate of the fault was lifted and

![Figure 1. Fault systems in the Dachaidan area.](image-url)
denuded as a whole, and the Mesozoic was largely absent in the bulge area. The middle part of
the Himalayas (Oligocene–Pliocene) and the Maxian fault continues to be active, showing
the characteristics of synsedimentary faults. The thicker Oligocene–Plezoic strata are depos-
ited in the western Yunnan sag, and the Mabei bulge area is characterized by drape sedi-
mentary characteristics. Late Xishan (Quaternary) under the strong squeezing action of the
northeast–southwest direction of the Qilian Mountains and the north–south direction of the
basin, the Maxian fault is strongly thrust, accompanied by left-handed compression char-
acteristics, and the Mabei bulge is placed in the western Yunnan Depression.

**Fault distribution characteristics**

The zoning and partitioning of the faults in the study area can be clarified through an
analysis and description of the three major fault systems in combination with the prepara-
tion of a fault system map.

**Zoning.** The main fault and the fault systems display south–north zoning, primarily con-
trolled by the basin margin and the intra-basin Southern Qilian, Sainan, Lvnan, and
Xitieshan Mountains, along with other mountain-controlling faults. The basin-margin
thrust nappe fault zone is comprised of the basin-margin Southern Qilian Fault and the
Qaidam and Hongshan Faults derived from it. Beishan Jurassic outcrops such as eastern
Yuka, Kuerleike Mountain, and the Hongshan syncline are clamped between the fault
zones. The intra-basin Lvnan thrust fault zone is composed of the mountain-controlling
Lvnan Fault and its associated Lvbei piedmont thrust fault and has a NW strike that
gradually transitions to nearly EW. The intra-basin Xitieshan Mountain fault zone is
made up of Xitieshan Mountain and the Xitieshan Mountain northern piedmont zone
thrust belt fault derived from it, making an inverted “Y” shape in combination, which its
strike is NW and extend length is over 40 km.

**Partitioning.** The study area is subject to dextral compression torsion from the Southern
Qilian Fault and is segmented into a series of rhomboid fault blocks under the joint
action of the leverotatory compression torsion on the Maxian and Lvnan Faults. Fault
development and the combination of structural styles differ among different fault blocks. A
series of NW-striking low-angle thrust faults have developed inside the Yuka Depression
under the action of the Sainan Fault thrust and the presence of a plastic Jurassic stratum,
forming an enclosed area clamped between the Sainan and Southern Qilian Faults and
controlling the formation of three major anticlinal zones, including the Mahaigaxiu zone.

The Dachaidan Depression, an enclosed block clamped between the Southern Qilian and
Lvnan Faults, has mostly developed through high-angle thrust faulting. The joint action of
dextral compression torsion on the Southern Qilian Fault and leverotatory compression
torsion on the Lvnan Fault have resulted in clear fault compression torsion characteristics;
this section has a NNW-striking “flower-like” combined style.

The Hongshan–Xiaochaidan Depression is not affected by intra-basin mountain and is
mostly dominated by thrust faults. A series of NW back-thrust faults have developed under
the combined action of the basin-margin to intra-basin basement slip fault and the
Xiaochaidan Fault, leading to a combined “Y” and inverted “Y” combined pattern.

The Mabei salient developed through a series of associated compression torsion faults
related to a “leverotatory” strike-slip under the leverotatory compression torsion of the
Maxian Fault. The associated faults converge in the direction of the Naxian Fault and are scattered toward the SE Gaqiu depression, so that they are distributed along the Maxian Fault in a “brush shape,” forming an obvious dextral compression torsion fault system together with the Maxian Fault.

**Structural modeling and analysis of the piedmont zone**

**Steps and methods**

Structural modeling was carried out through a comprehensive analysis of the surface and subsurface, shallow and deep structures, and seismic and non-seismic data. Tectonic phenomena were initially interpreted on the basis of surface geological maps, which provided information regarding the regional structural configuration and the characteristics of the basin–mountain boundary. A section was then selected for field investigation according to seismic and non-seismic (gravity, magnetism, electricity, etc.) data, and comprehensive analysis was carried out on the results of the field investigation for both seismic and non-seismic sections in order to establish multiple possible interpretations. Finally, a reasonable structural model was established by applying fault-related wrinkle theory. The structural model was required to meet the following conditions: (1) reasonable interpretation of the observed surface and subsurface structures and approximate representation of the structural characteristics of the tectonic zone; (2) capable guidance in seismic interpretation; (3) capable balancing of complex tectonic deformation; and (4) capable prediction of structures similar in type to those upon which the structural model was established (He et al., 2005).

**Structural modeling of the piedmont zone**

The tectonic zone that was most representative of the basin margin and intra-basin piedmont was selected on the basis of the three major fault systems previously identified. Structural modeling and analysis of its deformational characteristics was carried out.

**Structural modeling of the basin-margin piedmont**

**Qaidam piedmont-Eastern Yuka tectonic zone.** Outcrops of the Middle Jurassic Dameigou Formation are found in the Qaidam piedmont, contacting the Ordovician series of Qaidam Mountain at thrust faults. There is strong tectonic deformation of the Jurassic, resulting in an anticlinal interphase structure. Due to slipping at the coal seam, a small thrust nappe structure developed within the Middle Jurassic series, which wrinkled the coal seam and locally thickened the strata (Figure 2).

Structural modeling was performed by integrating the results of field investigation, seismic and electrical data, and data from numerous coal boreholes by the following five-step method: (1) the large-scale fault was identified on the basis of the dissection of surface structures in combination with the seismic data. The mountain-controlling Southern Qilian Fault was identified by field geological investigation and characterized as being steep in its upper region and gentler at deeper depths; (2) the geological structure was determined on the basis of seismic data in combination with electrical data. Data from the 338-line seismic and electrical sections showed the eastern Yuka fault zone to be a piggyback-like basin forming a two-way hedging structure with the Lvbei Fault derived from the Lvnan back thrust; (3) stratigraphic attributes of the fault were determined on
the basis of drill wells and outcrops. In Qaidam Mountain and the Lvliang piedmont, the Jurassic series form the hanging walls of thrusts, and the Yudong 1 and DY1 boreholes revealed the stratigraphic sequence expected in the autochthonous footwall sedimentation; (4) small-scale faulting was identified and characterized by analysis of drilling data. Fault development in the Jurassic system was characterized on the basis of core descriptions, lithological mutation, and dip direction, and vertical and lateral changes in the dip angle at 20 coal drill holes. Determination of the fault combination was guided by the fault interpretations and by wrinkle theory; (5) outcrop deformation was field-investigated to guide modeling. Field geological investigation showed that the Qaidam piedmont has a thrust nappe structure, with Proterozoic metamorphic rock thrust over the Middle Jurassic strata. ZK36-5, ZK40-11, and multiple coal boreholes revealed a sequence comprising an upper metamorphic rock and a lower Middle Jurassic stratum. An imbricated thrust structure developed in the Middle Jurassic series, making the strata dip more steeply (40°–75°); multiple coal drill holes revealed a brecciated zone within the fault and that the fault surface features compression wrinkles and striations. A back-thrust structure formed at the piedmont due to the influence of the Lvbei Fault, and the Jurassic strata was lifted to the surface; ZK7-2 and multiple drill holes revealed Jurassic strata in the hanging wall of the back-thrust. The wrinkles in the Jurassic strata showed intense deformation, and ZK3-8 revealed that they feature multiple occurrences of metamorphic rock, indicating multiple instances of basement-involved tectonic deformation; the Jurassic stratum revealed by ZK1-1 was clearly thickened, particularly when compared with the adjacent well, and the thickness of the coal seam was also clearly increased. This localized variation in the thickness of the compression wrinkling suggested multiple superimpositions.

An interpretative model of the Yuka eastern tectonic zone of the Qaidam piedmont was developed through the establishment of a lattice of the eastern Yuka tectonic zone in combination with seismic section facies (Figures 1(A–A’) and 2). On the whole, the eastern Yuka tectonic zone, controlled by the Southern Qilian and Lvnan back-thrust faults, forms a two-way hedging structure. Its deformation can be characterized as thrust-to-thrust nappe to competent fold from the basin margin to the intra-basin region. The piedmont has developed through the formation of basement-involved thrust nappes, with Proterozoic
metamorphic rock thrust over the Middle Jurassic series to a maximum distance of 3 km, forming a piggyback thrust nappe. The Jurassic system is internally dominated by imbricated thrusting, with strata superimposed in a complex sequence. Drill hole ZK40-9 showed the presence of the Quaternary conglomerate in the Jurassic system, indicating that the Quaternary system was involved in the deformation, so that it occurred later in this zone.

Hongshan–Lvcaoshan tectonic zone at the Kourerak Mountain front. Kourerak Mountain is formed of a series of N–W thrust faults. The southern part is thrust over Mesozoic–Cenozoic strata, and the Proterozoic Dakendaban Group metamorphic rocks at the mouth of a wide groove in the southeast of Hongshan are thrust over the Middle Jurassic series. The Hongshan tectonic zone is located in eastern Kourerak Mountain and is a long-axis syncline striking NWW.

A number of boreholes have been drilled in this area, e.g. Hongshan #1 and ZK6-1. These allowed the Hongshan tectonic zone to be characterized, and a tectonic model of the Kourerak Mountain Piedmont Zone was developed (as shown in Figures 1(B–B’) and 3) with the aid of 2D seismic and electrical data. The Hongshan–Lvcaoshan tectonic zone features large thrust nappe structures that formed due to the effects of the Hongshan Fault in the front row of the South Qilian Mountains. For example, the Kourerak Mountain and Hongshan synclines are thrust nappe structures on the hanging wall of the fault. Hongshan, in particular, is a mountain formed by the development of synclines. Drilling and seismic and electrical data all confirm the development of this thrust nappe structure. The Hongshan Shen #2 extends from the Jurassic Hongshuigou formation in the hanging wall to the palaeogene Lulehe formation in the footwall, with a fault depth of 3950 m. Hongshan #1 enters the Middle Jurassic in the footwall from the Cretaceous system in the hanging wall, with a fault depth of 3240 m. The depths of ZK8-1 and ZK6-1 at the front of Kourerak Mountain are 1217 and 952 m, respectively. These have not penetrated through the Tertiary system, indicating that the footwall of the Hongshan Fault contains relatively intact
Mesozoic–Cenozoic strata. The structural features are particularly evident in the interpreted section at line 428. The Hongshan Fault is steep in its upper reaches and gentler at deeper depths, and the Hongshan syncline takes a thrust nappe structure in the northeast, with relatively intact Mesozoic–Cenozoic strata preserved in its footwall.

**Intra-basin structural modeling of the piedmont.** Landforms such as Pingdingshan, Gaqiu, Yema, and Xiaochaidan successively developed in front of Lvliangshan and Xitieshan in the basin. For this paper, the Pingdingshan tectonic zone, located at the intersection of the Lvnan and Maxian Faults, was taken as an example for structural analysis and modeling.

The Pingdingshan landform has a N–W long-axis anticlinal structure and is characterized by the opposite arrangement of anticlines. A structural model of the region was established on the basis of data including that from 3D seismic, electrical, and gravitational investigations and analysis of the Pingdingshan tectonic zone. Interpretation of seismic Line 328 (Figures 1(C–C’) and 4) indicated that geological structures divide this zone into three layers, i.e. from bottom to top: (1) Mesozoic–Cenozoic autochthonous deposits in the footwall of the Maxian Fault (Gaxi Depression), (2) a Proterozoic and Mesozoic triangle wedge nappe and Tertiary autochthonous deposit between the Maxian and Lvnan F1 thrust faults with the Pingdingshan anticline earth surface nappe in the hanging wall of the Lunan F1 fault, and (3) the Lvliangshan nappe on the hanging wall of the Lvnan Fault.

Combined inversion of gravity, magnetic, electrical, and seismic data was used to verify the rationality of the interpretative model. Based on the inversion of gravity and seismic data and measured data from the well, the density of the Proterozoic bedrock was established to be 2.72 g/cm³, the Gaxi Depression Mesogenic to be 2.60 g/cm³, the Tertiary system to be 2.35–2.42 g/cm³, and the pre-Tertiary triangle wedge nappe to be 2.55 g/cm³. Results of the inversion showed a goodness of fit of the gravity anomaly curve calculated by the model and the actual measurements, thereby verifying the rationality of the interpretative model (Figure 5).
The above inversion showed that, in the hanging wall of the Maxian Fault, excluding the Tertiary system that has a low-density body, the density of the pre-Tertiary nappe is higher than that of the Tertiary system and lower than that of the Proterozoic. The triangle wedge is, therefore, presumed to be the Mesozoic nappe, the formation of which was controlled by the Maxian Fault in the Late Yanshan Mountain Period.

Structural style and distribution

Structural style

On the basis of field surveys in the outcropping area and a comprehensive interpretation of the seismic and electrical data, the structural deformation in the Dachaidan area was divided into three types: compressional, extensional, and strike-slip structures. Some complex tectonic zones were formed through the interplay of different types of structural deformation. A total of three categories and four subcategories (eight structural styles in total) were identified in the research area, and the three major types of structural deformation were observed to occur both independently and in vertical stacks (Wang et al., 2005). Even where there was the same type of structural deformation, there were significant differences in the structural styles of the zones at different depths or levels (e.g. Yukadong and Hongshan tectonic zones at the basin margin).

Figure 5. Gravity-constrained inversion of the Pingdingshan tectonic zone at the Lvliang mountain front.

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Prominent features of structural style and zoning in the research area were analyzed. The piedmont thrust nappe belt on the basin margin is generally made up of imbricated thrusts and a thrust nappe belt in the basin duplex. The piedmont thrust in the basin features mainly structures such as hedging structures, lifting structures, fault-bend folds, and fault propagation folds, while the anticlinal thrust belt in the basin features lifting structures and fault propagation folds. The Mabei Bulge and Dachaidan Depression in the basin mainly display a flower structure (Figure 6).

Analysis of the structural evolution
The superposition of multiphase tectonic movements formed a rhombic structural pattern, split into sections from east to west and belts from south to north. Borehole data showed substantial variation in the stratigraphic distribution of different structural units, indicating corresponding differences in the transformative and deformational impacts of the multiphase tectonic movements of the different blocks. A SW–NE profile along the Hobson Depression–Xitieshan-Hongshan Depression–Qilianshan was selected to study the structural evolution of the area (Figure 1(D–D’)) and analyze how these structural changes
controlled stratum development and residual distribution, structural deformation, and the geological structures visible today (Figure 7).

The Mesozoic–Cenozoic structural evolution in the Dachaidan area can be divided into four stages. The first was the Early-Middle Yanshan Period (Jurassic-Lower Cretaceous) stage, which featured extension, weak fault depression-extrusion, and deposition in depressions (Duan et al., 2007; Hu et al., 1999, 2002). The early Jurassic was characterized by extensional rifting, and the Lower Jurassic was only found in the Hongshan Depression. In the Middle Jurassic, stable lacustrine basin deposition occurred in depressions. The range of deposition expanded over time, starting with depressions such as Hongshan and Yuka, and with the Hongshan Depression expanding into the Xiaochaidan area. In the Late Jurassic-Lower Cretaceous, extrusion became weak extrusion depression, accompanied by deposition over a wide basin region.

The second stage was the Late Yanshan Period (Upper Cretaceous), which was controlled by the pronounced extrusion in the Kunlun and the Qilian Mountains (Wang et al., 2006; Zeng et al., 2002). Under strong thrusting in the South Qilian Mountains.

Figure 7. Sections showing the SW-NE tectonic evolution from the Huobuxun Depression to the Xitieshan–Hongshan Depression.
and on the Sainan, Lvnan, and Xinan Faults, bulges formed in regions such as Lvliangshan and Xitieshan. The Mesozoic on the fault hanging wall was denuded to different levels, controlling its residual distribution.

The third stage was Early Himalayas Period (Paleocene–Miocene), the regional tectonic compression was weakened, mainly due to differential settlement, no large-scale tectonic deformation occurred, and the ancient Gushixin was widely accepted from the basin edge to the basin. In the Paleozoic–Oligocene, the Hongshan sag was characterized by inherited settlement; in the Miocene, the structural inversion occurred in the Hobson and Hongsan sag, and the Hobson sag in the basin began to settle and accepted thick layers.

The fourth stage was the Middle Himalayan Period (the end of the Pliocene). Under the influence of NE–SW extrusion, fault control by the mountains and depressions occurred on a large scale and internal fault activity and structural deformation intensified. A relatively broad and gentle thrust belt was formed at the basin margin or in the basin. The hanging wall of the thrust belt and the Palaeogene–Neogene at the top of a pop-up structure in the basin were denuded to different levels. Most of the Neogene System was denuded, forming a regional unconformity between the Palaeogene–Neogene and Upper Quaternary.

The fifth stage was the Late Himalayan Period. Large-scale orogenic movements led to a sharp contraction of the Qaidam Basin, the rise of the Qilian Mountains at the basin margin, the formation of structures such as Lvliangshan and Xitieshan in the basin, and a relatively large-scale extrusive thrust deformation of the massif, piedmont zone, etc. Thrust nappe structures predominated at the basin margin and the mountain front, and extrusion thrust structures formed in the basin. The geological structural feature of bidirectional hedging was formed by the combined action of faults controlled by both the mountain and depression at the basin margin and in the basin and thrust faults.

Discussion

Control of the residual distribution of Middle-Lower Jurassic strata by Upper Cretaceous extrusion thrusting

The analysis above demonstrates the following: the development and distribution of Mesozoic strata were controlled by structural movement in the Early-Middle Yanshan Period; the residual distribution of the main Lower Jurassic (especially Mesozoic) hydrocarbon-generating beds was controlled by structural movement in the Late Yanshan Period, and the formation of geological structures and structural patterns was controlled by structural movement in the Late Himalayan Period.

The regional tectonic events at the northern margin of the Qaidam Basin in the Upper Cretaceous resulted in a loss of Cretaceous strata over the whole basin (Xiao et al., 2005; Wang et al., 2011). The Upper Cretaceous structural deformation was mainly dominated by integral lift controlled by fault blocks. The denudation of the Lower Cretaceous and other Mesozoic sequences is uniform in the same fault block, resulting in the contact between Cenozoic and Mesozoic strata being a parallel unconformity or small-angle unconformity. Sporadic Mesozoic residual strata have been found in the structurally uplifted areas in the basin or orogenic belts at the basin margin. The study results predict that the distribution of the Jurassic deposits has little relationship with that of the sub-structural belts of the present basin and the boundary of the present Qaidam Basin. In the Late Jurassic-Lower Cretaceous Period, there was primitive large-scale deposition at the northern margin of
the Qaidam Basin (Wu et al., 2011; Xiao et al., 2013; Yu et al., 2019). The sporadic present-day stratigraphic distribution is caused by late structural activity and denudation.

The Upper Cretaceous structural deformation resulted from the first stage of transformation of the sequence of Mesozoic deposits: fold deformation and denudation. This directly caused the formation of fault blocks with steep slopes and large-scale fold belts in the NW Mesozoic basin under the action of a series of thrust faults, including the South Qilian Mountains and the Lvnan, Maxian, and Xitieshan. Different degrees of denudation have resulted in NWW-trending stratigraphic overlap of the Mesozoic strata. As long as the Upper Jurassic or Upper Cretaceous remains, the Middle-Lower Jurassic will be well-preserved, provided it has primary deposits; otherwise, the Middle-Lower Jurassic will suffer denudation. Therefore, the Upper Jurassic-Lower Cretaceous is the first barrier protecting the Middle-Lower Jurassic from denudation. This was confirmed by the presence and absence of residual Middle-Lower Jurassic strata in boreholes and outcrops in the Yuka and Hongshan–Xiaochaidan Depressions.

The residual distribution of the Middle-Lower Jurassic is not directly related to the present depression nor is it completely constrained by the current pattern of depressions. The direct evidence is that the Middle-Lower Jurassic only remains in some piedmont zones, depression belts, and slope belts and that the relationship between the distribution of the Middle-Lower Jurassic and the current depressions is not one-to-one. This is mainly because, after the Late Yanshan Period, tectonic movement destroyed and reconstructed these Jurassic basins, and Himalayan tectonic movement once again divided and reconstructed the distribution of the Jurassic strata, forming the present pattern of residual distribution.

The Late Himalayan Period controls the depth of burial of the Middle-Lower Jurassic

The current structural pattern of the Dachaidan area resulted from tectonic movement in the Late Himalayan Period. The strike-slip thrust action at the Cenozoic north margin of the Qaidam Basin is the main reason for the formation of a “lenticular body” in the Jurassic stratigraphic sequence. It has also led to the development of a residual broken clamp Jurassic splice at the front of Saishiteng Mountain, the Qaidam Basin, Kourerak Mountain, and Lyliangshan, as well as to stripping, which has exposed generally lenticular coal beds, including North Yukashan, Datouyang, Kaiyuan, and Lvcaoshan. The uplift of the Late Himalayan basin margin and intra-basin mountain system once again transformed the distribution of the Jurassic primary deposit. The joint action of the Yanshan and Himalayan Periods was the main cause of the formation of the “lenticular body,” the formation of the broken clamp splice, and the stripping that exposed Jurassic structures at the northern margin of the Qaidam Basin. Furthermore, Himalayan tectonic movement controlled the current depth of burial of residual Jurassic strata, thus affecting the evolution of the source rock.

Conclusion

1. Three tectonic systems (compression, extension, and strike-slip) were identified in the research area and further divided into eight structural styles. The basin-margin thrust nappe belt at the mountain front primarily displays an imbricated thrust structure and an intra-basin thrust nappe belt duplex. The intra-basin thrust-fold belt at the mountain front shows various structures, including hedging structures, lifting structures, fault-bend
folds, and fault propagation folds. The intra-basin anticlinal thrust belt features lifting structures and fault propagation folds.

2. The Mesozoic–Cenozoic structural evolution in the Dachaidan area can be divided into five stages: the Early-Middle Yanshan Period (Jurassic-Lower Cretaceous) extension weak fault depression depositional stage, the Late Yanshan Period (Upper Cretaceous) extrusion uplift stage, the Early Himalayas Period (Paleocene–Miocene), the weak compression stage, the Middle Himalayas Period (Paleogene–Neogene) extrusion depression stage, and the Late Himalayan Period extrusion thrust stage.

3. Distribution of the Mesozoic primary deposit and the residual distribution of Late Yanshan deposits were mainly controlled by Later Triassic tectonic movement, whereas Late Himalayan activity was the main control of the differences in the depths of burial of the various structural units.

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