Research Article

Jurassic Provenance System and Its Geological Implication in Altyn Piedmont, Qaidam Basin

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A petroleum system originating from Jurassic source rocks exists in Altyn piedmont. However, the Jurassic formation in this system is deformed by Yanshan-Himalayan tectonic movement, and related studies about its spatial distribution and sedimentary system are still highly controversial. In general, a systematic research on the provenance system helps precisely restoring the prototype basin. Based on the methods of seismic characterization, sedimentary analysis, and detrital zircon U-Pb dating (samples from several Altyn piedmont outcrops), this paper studied the provenances of Jurassic formation in Altyn piedmont and characterized their distribution from different aspects: (1) Lacustrine rift basin developed in the study area at early Jurassic, while the formation showed a saucer shape with its thickness decreasing and vanishing towards the center of the basin in the middle Jurassic; in summary, the Jurassic formation in Altyn piedmont could be divided into several parts due to their different characteristics in different periods. (2) The south part of the Jurassic deposition (south of Qingshuigou) could come from the east Kunlun terrain; the middle part (Yueya mountain to Dongping area) however could be from several provenances, including the east Kunlun terrain, the surrounding plutons, and the Altyn fault; the north part (Niudong to north Lenghu area) is mainly related to the Altyn fault. (3) The Altyn fault, a regional fault system containing several strike-slip faults, is highly active since late Triassic and controls the current spatial distribution of the Jurassic formation; the faulted area in the piedmont could be separated into several parts with several different sources. (4) Compared to the southern and middle parts, the northern Jurassic deposition is relatively flat and contains wider and thicker source rock beds, which makes this area an important gas exploration target.

1. Introduction

The Qaidam Basin, surrounded by Altyn, Qilian, and Qunlun Mountain [1], is located in the northeastern Qinghai-Tibet Plateau. The conventional oil and gas reservoirs in the Qaidam Basin have reached $6.7 \times 10^9$ t [2], which makes this basin the 4th biggest onshore gas field in China. The Altyn Mountain is located to the northwest of the Qaidam Basin, and natural gas accumulation distributes in a large area in its southeastern piedmont. Middle-giant gas fields in this region such as Dongping, Niudong, and Jianbei have been explored since 2012, which are mainly supplied by Jurassic source rocks [3]. However, regional tectonic movement from Mesozoic to Quaternary lifted the Jurassic formation and led to heavy erosion and strong deformation. This makes it difficult to portray the stratigraphy, Jurassic prototype basin, and source rock development in Jurassic, thus resulting in restriction on further oil and gas exploration.

Based on seismic profiles and outcrop observation, previous studies have illustrated the spatial distribution of Jurassic formation and Jurassic prototype basin in the Altyn piedmont. However, these studies mainly focused on the structural analysis of several typical profiles. Besides, there
are multiple different conclusions of Jurassic prototype basin and sedimentary systems in west Qaidam Basin: (a) In Mesozoic, the strong compressive tectonic movement around this region led to thrusting up formations for several times, and Qaidam Basin was basically a foreland basin at this time [4–6]; (b) in Jurassic, the Qaidam Basin turned to a rifted or depressed basin formed in the lasting extensional environment in early Jurassic and transformed to a compressive basin as a result of the later structural inversion [7, 8]; (c) Qaidam Basin is a pull-apart basin formed by the control of the paleo-Altyn fault [9–11]. All controversial conclusions above about the Jurassic prototype basins and sedimentary systems led to great difficulty in precisely characterizing the distribution of Jurassic formation.

Detrital-zircon U-Pb geochronology has been widely used in restoring the prototype basin in recent years [12–15]. This technique semiquantitatively determines the prototype basin and formation distribution in complicated tectonic environment by comparing the zircon ages in different deposits. Based on the results of seismic characterization, sedimentary analysis, and detrital zircon U-Pb dating, this paper studied the Jurassic sedimentary systems in the Altyn piedmont, determined the Jurassic formation distribution and related provenance, then discussed the basin-range coupling of the Altyn Mountain and Qaidam Basin, and finally provided detailed information for further oil and gas exploration.

2. Geological Setting

The total natural gas reservoir in the Jurassic hydrocarbon system in Qaidam Basin has reached 1,145.5 bcm [16]. There are mainly two sets of major source rocks in the system: (1) lower Jurassic Huxishan dark mudstones and Xiaomeigou coalbed and dark-carbonaceous mudstones and (2) middle Jurassic Dameigou oil shale and coalbeds [17]. Current exploration in the system has proved the large oil and gas reserve in the paleo-uplift and later structural highs around the source rocks [18]. Besides, the distribution of Jurassic formation has been outlined; therefore, the exploration targets of natural gas are clear.

The Altyn fault belt is the northeast boundary of Qinghai-Tibet Plateau. It extends in northeast about 1600 km [19] and is composed of several sets of northeast strike-slip faults formed in different periods. The faulted area experienced several tectonic transformations [20–22]: (1) Archaeozoic to paleo-Proterozoic crystalline basement, (2) Mesoproterozoic passive continental margin, (3) late Neoproterozoic to early Paleozoic oceanic crust spreading, (4) Caledonian plate subducting and collision, (5) late Paleozoic to Mesozoic intraplate extension, and (6) Cenozoic basin development and later uplifting. Most scholars agreed that the Altyn fault systems formed in the collision of Indian Plate and Eurasian plate, and the Eocene uplifting and left-lateral strike slip lead to an average fault displacement about 400-500 km [23–25]. The Altyn piedmont is the large area in the west Qaidam Basin that borders the Altyn Mountain, which extends to Yueyashan slope to the west and Lenghu slope to the east. It could be divided into several substructural units as north Kunlun terrace belt, Yingxiongling-Mangya sag, Dongping nose structure, Yiliping sag, Niudong-Niuzhong nose structure belt, and north Lenghu slope (Figure 1).

**Figure 1:** Regional structural map of study area.

The Jurassic formation in the Altyn piedmont includes several belts and has outcrops at Alabastao to Qaidam Gate in the north, Honggouzi to Yueyashan in the middle, and Qingshuigou to Meiyaogou in the south. Previous research
pointed out that the Jurassic formation in the Altyn piedmont has been deformed in later tectonic movement. As a result, its current distribution is different from that before, so the current structural highs are not necessarily the Jurassic provenance [26].

3. Jurassic Stratigraphy in Altyn Piedmont

The Jurassic stratigraphy in north Qaidam Basin has been clearly illustrated in other papers. However, stratification of Jurassic formation in Altyn piedmont is still controversial. Based on previous studies, outcrop observation, and Mangya regional structural map from China Geological Survey, this paper proposed a stratification scheme for Jurassic formation: lower Jurassic Huxishan and Dameigou-a, middle Jurassic Dameigou-b and -c, and upper Jurassic Caishiling and Hongshuigou (Figure 2).

3.1. Huxishan Member. Huxishan Formation is locally distributed in Qaidam Basin. It is exposed in the north Qaidam but not exposed or drilled in Altyn piedmont.

3.2. Dameigou-a Member. Dameigou-a is a set of fluvial fan and fan delta deposits. Fan delta deposits in the study area are mainly distributed in lower Jurassic at Yihaogou and Hongshuigou area. At Yihaogou outcrop, the thickness of Dameigou-a reaches 1325 m and is unconformably covered by Hercynian granite. The lower part of Dameigou-a is composed of dark and greyish-green conglomerates, pebbly sandstones, and sandstones. The pebbles show low degree of rounding and simple constitution. At Etonbrac town outcrop, the greyish-green conglomerate in the lower part of Dameigou-a has a thickness of over 1000 m. The constitution of the rock includes granodiorite, dark volcanic rock, and vein quartz, similar to that of the underlying crystalline basement. The observations above show that the lower part of Dameigou-a was from a single provenance around and deposited in the process of basin filling up. The upper part of Dameigou-a shows smaller grain size, and its constitution is mainly dark and greyish-green sandstones and pebbly sandstones containing thin layer of dark carbonaceous shale. Dameigou-a is a set of deposits formed in the fan delta and fluvial fan environment.

3.3. Dameigou-b Member. Middle Jurassic Dameigou-b and -c were mainly distributed in southern and western Qaidam and Alabastao. Dameigou-b conformably covers Dameigou-a on the top, while unconformably covers the Ordovician Tanjianshan or early Paleozoic intrusive rocks at some part. Dameigou-b is a set of deposits formed in the braided river delta and lacustrine system. In Qingshuigou outcrop, Dameigou-b is a set of typical lacustrine deposits with a thickness of 1853 m, composed of dark and carbonaceous mudstones, carbonaceous (siliceous) slates, argillaceous siltstones, and silty mudstones. Dark oil shale was also observed at some points. Horizontal bedding is the main sedimentary structure in this Member, while incised valley that filled with pebbly sandstones develops at the bottom. At some outcrops in the area such as Hongshuigou, Meiyaogou, Linhaotao, and Chaishuigou, a set of coalbeds with a thickness of 80 m is exposed, while in Dameigou-a, there is no coalbed at all. Commonly, existence of coalbed is used to differentiate Dameigou-a and -b.

3.4. Dameigou-c Member. The distribution of Dameigou-c is confined to the Qingshuigou and east Shaliugou area. Dameigou-c conformably covers Dameigou-b above, and at Qingshuigou outcrop, its thickness is 468 m. The constitution of Dameigou-c includes phyllitic silty slates, carbonaceous slates, and siliceous slates with thin layers of dark middle-fine sandstones and pebbly sandstones, which marks Dameigou-c as the finest deposition with highest compositional maturity in Jurassic formation. Dameigou-c was formed in the braided river delta and lacustrine environment, and horizontal bedding is commonly observed.

3.5. Caishiling Member. Caishiling is widely distributed in this area. Core observations in well TM 1 show that there are red, brown, and grey conglomerates, glutenites, and slates, with thin layers of brown mudstones here. At Caishiling outcrop and well LI 1, there are more conglomerates, with smaller thickness; however, in well TM 1 in the southwest of the study area, Caishiling shows the characteristics of arid-semiarid braided river–braided river delta deposits. In the east Shaliugou outcrop in the piedmont, the deposits are finer in grain size, and its sedimentary environment turns to lake shore—shallow lake. At Caishiling outcrop, the environment further turns to braided river delta and lake shore, and in well LI 1, it turns to braided river environment. Sedimentary facies and lithology show a frequent horizontal shift in Caishiling formation.

3.6. Hongshuigou Member. Hongshuigou Member is mostly observed at Hongshuigou outcrop. Its constitution is mainly red and brown mudstones, argillaceous siltstones, siltstones, and fine sandstones with thin layer of conglomerates. Hongshuigou was formed in fan delta, lake shore, and shallow lacustrine environment, in which mostly fine deposit develops. The red color is a strong mark in analyzing spatial correlation of the formation.

4. Methods for Provenance System Analysis

Combined with outcrop observation and seismic profiles, this paper used methods of stratigraphy, paleocurrent direction analysis, and detrital zircon dating to determine the Jurassic sedimentary system and strata distribution.

4.1. Geophysics Analysis. Geophysics interpretation in this paper included paleo-source direction determination based on seismic profiles and paleocurrent direction analysis on well logs. Seismic facies in the Jurassic depression was characterized on the basis of seismic profile observation and interpretation and laid foundations for sedimentary facies descriptions in the Altyn piedmont. In the profiles at piedmont, S2S (source to sink) elements such as denuded zones, paleo valleys, and paleo slopes were characterized to determine the sources for each sedimentary system.
4.2. Sedimentary Description. Paleo-current and heavy mineral analysis was conducted in this paper. Paleo-current direction analysis is one technique that determines the direction of paleo slope and sources through observation and measurement of alignment of cross bedding, ripple mark, fossils, impression marks, and pebbles [27–29]. Considering previous studies on paleocurrent directions, this paper measured the paleocurrent direction in Hongshuigou, Aketidagou, Heishishan, Yihaogou, and Qingshuigou outcrops and determined the sediment transport direction.

Heavy mineral analysis has been commonly applied in the source direction analysis. Heavy mineral is the transparent or nontransparent mineral with density higher than 2.86 g/cm³ in sediments. Typically, the content of heavy minerals in sediments is less than 1%, which provides the information of rocks in the source. ZTR index (contents of
zircon, tourmaline, and rutile in transparent heavy minerals) is used to determine transport distance, with higher ZTR index indicating longer distance and higher constitution maturity. In this study, 10 kg of fine sandstone samples was collected in the outcrops such as Hongshuigou, Heishishan, and Aketidagou. Then, they were further observed under binoculars to separate and identify minerals. At least 500 samples were selected for each mineral, and their content was further calculated.

Sedimentary characteristics provide the information about transport direction in the center and margin of the basin, the inclination of the paleo slope, and geometry of deposits. However, this method cannot provide information about provenance location, source lithology, and structural backgrounds.

4.3. Isotopic Dating. Zircon is a commonly observed accessory mineral and is widely used in S2S analysis because of its strong weathering resistance and stable U-Pb isotope system. Current LA-ICP-MS is able to measure in situ isotope in one single mineral in a short time, so zircon is a good choice for sediment dating and source analysis. The results could be further applied to palaeogeography restoration and structural evolution analysis.

Zircon samples were collected in the middle-coarse sandstones at QSG-1 (N38° 33′ 9.93″, E90° 35′ 17.63″) and QSG-4 (N38° 33′ 13.93″, E90° 35′ 24.37″) in Qingshuigou outcrop. YYS-5 (N38° 42′58.16″, E91° 22′9.08″) in the north Yueyashan outcrop and core sample N-102-2 in well N102. 80-130. Zircon samples were collected in 2 kg non-magnetic constituent of heavy minerals in rock samples and dated at the Northwest University using LA-MC-ICP-MS (the sample points are shown in Figure 1). The diameter of the 10 Hz laser spot is 30 mm, and helium was used to transport the ablation waste. The 91500 Zircon was used as external standard, and the sample was measured at every 5 points; 29 Si was used as internal standard and NIST610 as external standard for element content. Detailed process, methods, and parameters see Prof. Diwu [30].

5. Results

5.1. Seismic Profile Interpretation. Seismic profiles here show several separate small-scale early Jurassic rifted lake basins in the south part of Altyz piedmont (south of Yueyashan), such as the small basins in Qingshuigou, Yihaogou, and northern Yueyashan. These basins are graben or half-graben controlled by deep faults, and in seismic profiles, they appear as wedges with larger thickness at Altyz piedmont and getting smaller towards basin center. Seismic reflection of these lower Jurassic wedges is characterized by weakly continuous and low amplitude and frequency and is truncated by the strong reflection of middle Jurassic coalbeds. Middle Jurassic formations show continuous, intermediate amplitude, and frequency in profiles and are conformably covered by Paleogene strata.

Seismic reflections of Jurassic strata across Yueyashan-Dongping are similar to those of the south part mentioned above, except for the rifted basins even smaller in lower Jurassic profiles and those basins with thinner middle Jurassic formations. However, middle Jurassic reflections are more continuous with higher amplitude, featured with wider range and greater thickness of coalbeds (Figure 3(a), A’). In the profiles across Niudong-Oboliang1# at north part of the study area, larger grabens and half-grabens develop in Jurassic strata (Figure 3(b), B’). Compared to other districts, lower-middle Jurassic formation here is thicker and wider, and the whole Jurassic strata get thinner towards Altyz piedmont. This shows that the north part of Altyz Mountain controlled and supplied the deposition in the study area in early Jurassic (Figure 3(c), C’).

It can be concluded from the seismic interpretation results that (1) different Jurassic basin-range coupling characteristics in Altyz piedmont help to separate the study area into 3 parts. In the south part, Jurassic strata is faulted at west and overlaps at east and gets thicker towards the mountain; in the Yueyashan district, the spatial distribution of Jurassic strata is stable, while in north part the strata gets thicker towards the basin center and is faulted at east and overlaps at west. A possible explanation for the different characteristics above may be the different source districts and original structures. (2) For lower Jurassic rifted basins, their coverage and thickness in the north and south are larger than that in Yueyashan. But in middle Jurassic strata, these three parts are basically consistent with each other in thickness, reflection, lithology, and sedimentary system. The study area may be depressed at this time, and flood lake basin developed, which was connected with the Jurassic formation in the north Qaidam Basin.

5.2. Paleocurrent Direction Analysis. On Yihaogou profile in the south part of Altyz piedmont, the oriented scour-deposit pebbles proved that the paleocurrent mainly flowed from west to east, indicating that the sediments were supplied by Altyz Mountain. On Hongshuigou-Caishiling profile, the direction of paleocurrent was northeast, indicating its main provenance was in the southwest, while some northeast directed current showed that the sediments here were partly supplied by the exposed rocks around. On Qingshuigou profile, the direction of paleocurrent was northeast as well, and this profile shared source area with Hongshuigou district considering its location related to the sedimentary area. On the contrary, the paleocurrent to the southeast of Hongshuigou flowed from southeast to northwest, indicating a provenance in the southeast (Figure 4).

The above results show that the dominant direction of paleocurrent is northeast, and the main provenance for the study area is Qimantag to east Kunlun. Some southwest directed paleocurrents reveals that some ancient rocks exposed around also supplied this area. In addition, in planar view, all directions of paleocurrent in the middle part point to Qingshuigou, indicating that this is a Jurassic sedimentary center. The disorder directions around Yueyashan show that various districts supplied this area, and it is deduced that Yueyashan is another sedimentary center except Qingshuigou.

5.3. Heavy Mineral Combination

5.3.1. Lower Jurassic. Heavy mineral combination in lower Jurassic in Yihaogou profile is zircon+ titanite+
Late Jurassic paleocurrent rose diagram

Early Jurassic paleocurrent rose diagram

Figure 3: Jurassic seismic profiles at Altyn piedmont (see Figure 1 for the section location).

Figure 4: Jurassic current directions in west Qaidam Basin (part of the data comes from Bradley and Ulderico [31] and Duan et al. [32]).
titanomorphite + apatite, indicating an acid magmatic and intermediate-low grade metamorphic source. Unstable heavy minerals such as epidote and garnet show the existence of high-grade metamorphic rocks in the source. On the north Yueyashan profile, lower Jurassic heavy minerals contain hematite and limonite, zircon, and rutile, which is different from that in Yihaoqou profile, indicating a different source at this place. The existence of hematite and limonite may be related to the arid-semiarid sedimentary environment, which coincides with the results of sedimentary facies characterization. Lower Jurassic heavy mineral combination at Niudong profile contains unstable authigenic minerals such as barite and pyrite, indicating that the profile is close to the source, which coincides with the seismic interpretation results. On Yueyashan profiles in the middle part of the study area, the whole Jurassic formation shows high unstable heavy mineral content, showing a deposit supplied by close source.

In summary, Jurassic heavy mineral combinations at the three parts of Altyn piedmont highly differ from each other, indicating that these parts are supplied by different sources. The south part shows stable heavy minerals, and it may be supplied mainly by Qimantag-east Kunlun orogen and partly by Altyn Mountain. The Yueyashan district is supplied by Altyn Mountain and exposed rocks around. The evidence mentioned shows that several small-scale sedimentary basins existed at early Jurassic in Altyn piedmont, and each of them was supplied by independent sources (Figure 5).

5.3.2. Middle Jurassic. Two middle Jurassic heavy mineral combinations develop on Qingshuiguou profile: (a) zircon (highest content) + titanomorphite + tourmaline and (b) hematite and limonite (highest content) + zircon + titanomorphite + apatite. This indicates that this place is supplied by several low-intermediate grade metamorphic and sedimentary sources, with low content of midacid magmatic rocks. Different source areas show that Qingshuiguou was the sedimentary center. At the top of the middle Jurassic, the content of titanite that indicates midacid magmatic source increases; in addition, small amount of unstable minerals as pyroxene and authigenic minerals as barite and pyrite exists, indicating that the active structural movement in middle Jurassic provides new source areas around. It is deduced that the source area was east Kunlun-Qimantag.

Mineral combinations in the south Yueyashan district is different from that in the south part of study area. The content of titanomorphite and rutile largely increases, and small amount of picotite exists. This indicates a metamorphic source, with some midacid magmatic rocks. All evidence above proved that south Yueyashan was supplied by another source at middle Jurassic. Considering the result of paleocurrent analysis, the provenance of south Yueyashan may be on the paleo Altyn Mountain west and north of it.

5.4. Zircon U-Pb Dating

5.4.1. Results of Each Sample

(1) QSG-1# at Qingshuiguou Profile. The sample was collected in middle Jurassic formation, and 110 effective measurements were selected (Figure 6). The age of zircon ranges 229.3-2618.7 Ma and shows 4 breaks:
201-272 Ma (peaks at 254 Ma), 383-511 Ma (peaks at 421 Ma), 882-1098 Ma (peaks at 911 Ma), and 1203-1811 Ma (peaks at 1423 Ma). Zircon shows clear oscillatory zones in CL images, and younger zircons have light metamorphic rims (Figure 7)

(2) QSG-4# at Qingshuigou Profile. This sample was collected in middle Jurassic at Qingshuigou, and 110 effective measurements were selected (Figure 8). The age of zircons ranges from 223.2 to 2405.9 Ma, and their age spectrum is similar to that of QSG-1#. 4 breaks were recognized: 223-288 Ma (peaks at 223 Ma), 412-496 Ma (peaks at 483 Ma), 799-987 Ma (peaks at 945 Ma), and 1322-1791 Ma (peaks at 1693 Ma). A minor break from 2259 to 2434 Ma was also recognized. Zircon shows typical oscillatory zones in CL images, and younger zircons have light metamorphic rims (Figure 7). The similar age spectrum of QSG-1# and QSG-4# shows a stable source that supplied this area

(3) YYS-5# at North Yueyashan. This sample was collected in lower Jurassic at Yueyashan profile that neighbors Alabastao fold in Altyn Mountain, and 102 effective measurements were selected (Figure 9). The age of zircons ranges from 238.6 to 2601.1 Ma. The curve shows major peaks at 261 Ma, 281 Ma, and 456 Ma and minor peaks at 991 Ma, 1884 Ma, 2241 Ma, and 2521 Ma. This indicates that this area was supplied by several sources, which is identical to paleocurrent and heavy mineral analysis above. Most zircons in this sample have magmatism origin, and a few of them have metamorphism origin (Figure 7)

(4) N-102-2# in Well N102. This sample was collected in lower Jurassic in well N102 in the north of Qaidam Basin, and 76 effective measurements were selected (Figure 10). Their age spectrum is different from that of the other samples. The age of zircons ranges from 115.9 to 1652.7 Ma, with major peak at 279 Ma and minor peak at 411-455 Ma, and only one Neoproterozoic zircon was recognized. A few Yanshanian zircons exist in this sample that may be related to slight structural deformation after Jurassic, which is distinctive to other samples (Figure 7)

5.4.2. Implications to Sources. The study area neighbors paleo orogens such as Altyn Mountain, Qilian Mountain, and east Kunlun Mountain. Combined with 1654 measurements [33-35] of zircon age in this area and neighbor areas that were published previously, this paper recognized 4 potential sources including eastern Kunlun-Qimantag, northern Altyn, the east of southern Altyn fault, and southern Altyn fault (Figure 11).

The age of zircons in the neighbor areas distributes in Hercynian and Caledonian period, with peaks at 251 Ma, 270 Ma, 420 Ma, and 451 Ma. From Paleozoic to Triassic period, Qaidam Basin was a paleo-continent, and Paleozoic fold basement and Proterozoic crystalline basement formed the basement of current basin, which leads to the existence of some Neoproterozoic zircons with weak peaks at 838 Ma, as well as a few Paleoproterozoic to Archeozoic zircon records. The ages of zircons in the east of south Altyn fault were distributed in Caledonian period with a peak of 454 Ma, and some records fall in the range of 240-360 Ma with two weak peaks of 265 Ma and 348 Ma; few zircon samples’ ages fall in Neoproterozoic or older interval. In the west of south Altyn fault, the ages of zircons were mainly distributed in Caledonian and Neoproterozoic (500-1000 Ma) period, while none fall in Hercynian period. The difference in zircon ages in the two sides of south Altyn fault is related to the breakup of Gondwana continent. After the breaking up, the east and west sides of south Altyn fault were separated into two landmasses: Altyn-Qilian-Quanji and Qaidam. In the north Altyn, the ages of zircons were mainly
distributed in two intervals: 343-546 Ma and 1270-2270 Ma. Many samples fall in Proterozoic-Archeozoic period, indicating that this area is the main part of Altyn fault.

Zircon age of QSG-1# shows two peaks: 254 Ma and 442 Ma, similar to the zircon age in samples of east Kunlun-Qimantag, which were mainly distributed in Caledonian period with a peak of 454 Ma. Moreover, QSG-1# has a small peak at 1423 Ma. Combined with the CL image observation, it is concluded that this area was also supplied by magmatic sources. In another sample (QSG-4#) at Qingshuigou profile, zircon age shows similar spectrum to CX17-20# with two strong peaks at Hercynian and Caledonian period, indicating a stable source in east Kunlun-Qimantag that supplied this area at middle Jurassic. A small amount of Proterozoic zircons in the samples may be from southern Altyn.

Zircon age in north Yueyashan (YYS-5#) shows a wide spectrum in 238.6-2601.1 Ma, with major peaks at 261 Ma, 281 Ma, and 456 Ma and minor peaks at 991 Ma, 1884 Ma, 2241 Ma, and 2521 Ma. This indicates that this area was supplied by several sources. It is notable that Neoproterozoic zircons are commonly found in the samples, while the
exposed area of Neoproterozoic basement is mainly distributed in middle Qilian landmass, as proved by many previous studies. The Precambrian metamorphic basement formed at Jingningian Period (800-1000 Ma). Altyn, Qilian, and Quanji landmass did not fully converge together until the Indosinian period, and the west of Altyn fault therefore contributed to the sediments in the study area. Moreover, the two peaks at Archeozoic period indicate that north Altyn Mountain also contributed to the Jurassic sediments in Yueyashan. This indicates that this area was supplied by several sources, which is identical to the paleocurrent and heavy mineral analysis results.

Zircon ages at Niudong-Eboliang district range from 115.9 Ma to 1652.7 Ma, and this period is mainly in Hercynian period, indicating a single source for the sediments. Neoproterozoic or older zircon is rarely seen, and the peak is at 279 Ma. Former studies showed that Hercynian rocks are exposed at middle Altyn Mountain in a large area [36], whose age coincide with the peaks of zircon age in the sample, indicating that the Jurassic deposits in Niudong-Eboliang district were supplied by Altyn Mountain on its west. Altyn Mountain is not a source for the north Qaidam Basin because of the development of Lenghu sag, which is proved by the zircon age. Two Jurassic sedimentary systems therefore exist in the whole region, where the sedimentary basins in Altyn piedmont are smaller, which are controlled by Altyn strike-slip faults.

6. Discussion

6.1. Distribution of Jurassic Formation. Experiments, observations, and analysis above proved that Jurassic formation is separated into 3 parts in Altyn piedmont: the south part...
(the district from Qingshuigou to Yueyashan), the middle part (the district from Yueyashan to north Lenghu sag), and the north part (the district from Lenghu sag to Niudong). Sedimentary sources for the three part are totally different.

6.1.1. Original Sedimentary Environment of Middle-Lower Jurassic Formation in the South and Middle Part of Altyn Piedmont. Several small-scale rifted basins developed separately at early Jurassic period in the south and middle part of the study area, such as Yihaogou, Yueyashan, and Meiyaogou. Further, in the middle Jurassic period, the area of the basins increased, and the activity of faults decreased. Through the process of basin filling up, the paleo topography was flattened then, and the depth of the water got deeper. The alluvial environment in the early Jurassic period was gradually transformed to braid delta and lake environment, and a set of coalbeds were deposited across the whole area in the warm and wet weather.

The south and middle parts of the study area were supplied by several sources in the lower-middle Jurassic period. Instead of the Altyn Mountain, Qingshuigou area in the south part was supplied by east Kunlun-Qimantag in the middle Jurassic period. Seismic profile shows that the middle Jurassic formation pinches out southeast at Shizigou-Nanyishan. However, alluvial fans develop at Etonbrac town outside the basin, indicating the sediment contribution is from paleo Altyn fault, which proves complicated influence of Altyn fault on sedimentary sources.

The Yueyasha district in the middle part was supplied by east Kunlun-Qimantag and some exposed basements around Altyn Mountain. In seismic profile, the rifted basin is smaller, along with more complicated fault systems. Field observation showed multiple directions of paleocurrent, indicating the middle part of the study area might be the transfer zone of the Altyn strike-slip fault systems.

In the north part of the study area, several sedimentary basins developed at the early Jurassic period, such as Ebolliang structure 1#, Pingdong, and Kunteyi. However, different from the southwest Qaidam Basin, these basins were partly connected, which resulted in a larger sedimentary area. Its sedimentary source was controlled by the boundary of the basin (Figure 12).

6.2. Mesozoic Tectonic Framework of Altyn Mountain. Since Phanerozoic period, the Altyn fault has experienced several times of tectonic deformation. As concluded by some studies [37], the Altyn fault zone was uplifted due to the collision of the Indian Plate and the Eurasian plate, and it was not highly active. It was not exposed and supplied the sedimentary basins around until 65 Ma. However, the thermochronology data of the samples from Jolivet et al. [38] recorded a tectonic movement from late Triassic to early Jurassic period, which is the result of the collision of the Qiangtang plate.
and the Kunlun plate. Roger et al. [39] found several geologic features indicating the activity of Altyn fault in Triassic period. Wang et al. also found records of sinistral strike-slip shearing of Altyn fault in 250-230 Ma and sinistral strike-slip deformation in 100-89 Ma.

Through all analysis and results above, it is concluded that the Altyn fault was active already in the late Triassic; otherwise, the Jurassic sedimentary systems would be simpler. The south part did not experience heavy tectonic movement in the Indosinian-Yanshanian period, while in the early Jurassic, large scale rifed basins developed, along with thick deposits. In Dongping district in the north, the Altyn fault was more active in late Triassic and led to complicated sources and smaller basins in Yueyashan; while in Niudong district, the Altyn fault became the exposed sedimentary source rocks for Jurassic deposition and may be highly uplifted. In the intersection area of the two strike-slip faults, the stress field resulted in several pull-apart basins, such as Qingshuigou and Yueyashan; each basin (or sag) had its own provenance systems. At the end of the strike-slip fault, large-scale extensional imbricated structures develop, such as the Jurassic half grabens in Niudong and north Lenghu. Generally, these structures were supplied by a single sedimentary source. Duplex structures also develop at the end of the strike-slip faults: in the south Qaidam Basin, the Jurassic coarse-grain depositions are separately distributed in a small scale. In the northeast profile in Etonbrac town, a set of alluvial fan deposits develop with a thickness larger than 700 m, which is not spatially related to Qingshuihe depression: the two sets of deposition may be two separate depression systems.

In summary, the Altyn fault was a regional strike-slip fault in the Mesozoic period, which controlled the Jurassic basin type and distribution. In addition, the fault was separated into three parts, totally different from its framework in the Cenozoic period. The Altyn fault is located in the intersectional part of Qaingtang, Songpan-Ganzi, Qaidam, Tarim, and Siberian terrains; at early Jurassic (180 Ma), along with the splitting of the Gondwana continent, the middle Tethys Ocean started to close, and the Qunlun-Qaidam-Qilian plate began to converge with the Tarim and Yangtze plates. At this time, the south part of Altyn fault uplifted, while the central orogen in the north part was in a stable postcollision period. Complicated tectonic framework resulted in the separation of the Altyn fault (Figure 13).

6.3. Oil and Gas Exploration. According to the results of resources evaluation (4 times in all), natural gas reserve in Jurassic traps in Altyn piedmont reaches more than 620 billion m$^3$. However, the proved exploration rate is less than 2%, indicating a huge potential in the future. The main large and midsize exploited oil and gas fields in front of Altun Mountain, such as Dongping, Niudong, and Jianbei, are those close to the source rocks. Besides, they are also located in where fault depression source rocks of early Jurassic developed pretty well. Both situations are of great significance for oil and gas accumulation. At the same time, there is also great potential to explore the unconventional oil and gas of Jurassic source layers. In conclusion, the distribution of Jurassic main depressions predicts the location of oil and gas reservoirs. The south part of the Jurassic formation has been substantially exposed to the surface, and its boundary extends into the Qaidam Basin, results in high exploration risk. The structure of the basins in the middle part is complicate, and the scale of these basins is small, while in the Yueyashan structure, the source rock is studied in detail, showing values for development. The boundary of Jurassic deposition in the north part is at the Altyn piedmont, and the Jurassic sags are well preserved with large scale, which makes this district an important target in the future.
7. Conclusion

It is concluded that the Jurassic basins in the Altyn piedmont are the continental pull-apart basins in the strike-slip settings:

(1) Seismic profiles show that the early Jurassic deposits develop in a wedge-shape with contemporaneous normal faults; the middle Jurassic formation shows a saucer shape with its thickness decreasing and vanishing towards the center of the basin, indicating enlargement of Qaidam Basin and stable spatial distribution of Jurassic formation.

(2) Sedimentary source system is complex across the whole area; the southern part of the Jurassic deposition (south of Qingshuigou) could originate from the east Kunlun terrain, and the thickness of the deposition decreases towards the center of the basin; the middle part (Yueya mountain to Dongping area) was supplied by several sources, and the rifted area is smaller in seismic profile; the northern part (Niudong to north Lenghu area) deposits mainly come from the Altyn fault.

(3) The complex strike-slip fault systems of the Altyn fault controlled the spatial distribution of the Jurassic deposition; the Altyn fault is located in the intersectional area of several terrains and is composed of several Triassic faults, which can be separated into several parts.

(4) The northern Jurassic deposition is relatively flat and contains wider and thicker source rock beds, which makes this area an important gas exploration target.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


