Jurassic continental coal accumulation linked to changes in palaeoclimate and tectonics in a fault-depression superimposed basin, Qaidam Basin, NW China

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The Middle Jurassic Aalenian–Bajocian stages represent the tectonic transition period for the group of Jurassic sedimentary basins in northwestern China and include accumulation of the most important recoverable coal seams. Geological data from borehole cores, well loggings and rock-mineral determination in the Aalenian to Bajocian-aged Dameigou Formation in the Yuqia coalfield, Northern Qaidam Basin were employed to unveil the relationship between coal accumulation and changes in palaeoclimates and provenance tectonic activity. The results identify six kinds of lithofacies from fluvial and lacustrine sedimentary systems, and allow the Dameigou Formation to be divided into two third-order sequences (SIII1–SIII2) and their corresponding system tracts by regional unconformity surfaces, forced regression surfaces and their correlative conformity surfaces, and the abrupt shift surfaces of depositional facies. The main coals, the #7 and #6 seams, were deposited in a lake and swamp environments during lake transgression system tracts of SIII1 and SIII2, respectively. The varying trend of the Tectonic Index values indicate that the source area experienced strong tectonic activity from the SIII1 to the lowstand system tract of SIII2, and then gradually stabilized. The Mineral Alteration Index reveals that the climate during SIII1 was from dry-hot to humid-warm, and there is a climate cycle from dry-hot to humid-warm then a return to dry-hot in SIII2. During the faulting stage, the occurrence and termination of coal accumulation was in response to weakening and strengthening periods of tectonic activity respectively, while during the depression stage it was in response to the humid-warm and dry-hot climate respectively.

KEYWORDS
coal accumulation, fault-depression superimposed continental basin, Middle Jurassic, palaeoclimates, provenance tectonic activity, Qaidam Basin

1 | INTRODUCTION

As an important part of the global carbon cycle, coal accumulation represents a global geological event (Lu et al., 2016) sequestering atmospheric carbon dioxide from photosynthesis in terrestrial higher plants into coal seams by peatification and coalification. Large-scale coal accumulation in geological history was not limited to a single stratigraphical time interval, but consisted of a series of sub-level coal-accumulating events controlled by internals mechanism (Yang & Han, 1979). To help further understand the global carbon cycle through geological history, it is important to consider the causes of coal accumulation occurrence and termination.

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Coal accumulation is influenced by the relationship between rates of accommodation creation and peat accumulation (e.g., Diessel, Boyd, Wadsworth, Leckie, & Chalmers, 2000; Petersen & Ratanasthien, 2011). Bohacs and Suter (1997) and Holz, Kalkreuth, and Banerjee (2002) considered that peat can be preserved to form coal only when the overall rate in peat generation of accommodation approximately equals the accumulation rate of peat. Among them, the tectonic subsidence and base-level change are the main controlling factors of accommodation variation; the supply of plant availability provides material for the accumulation of peat (Xu et al., 2020). In continental lacustrine basins, the primary driving factors of base-level fluctuation include tectonic and climatic controls (Shanley & McCabe, 1994). However, the explanation for the occurrence and termination of coal accumulation is extensively at the qualitative descriptive level, in general expressed as ‘coal accumulation was an integrated product of palaeostructures, palaeoclimates, palaeoenvironments, and palaeo-plants’ (Liu, 1990; Phillips & Peppers, 1984). There are few reports of the occurrence and termination of coal accumulation and its response to the changes in palaeoclimates and provenance tectonic activity. Moreover, during practical analysis of coal accumulation, researchers tend to concentrate in a single fault basin or a depression basin, and coal accumulation models for fault-depression superimposed basin are frequently neglected.

During the Yanshanian movement, the Jurassic basins in northwestern China, for example, Qaidam Basin and Turpan-Hami Basin, generally underwent a tectonic evolution history from the fault to depression stage (Zhao, Qi, Xue, Meng, & Zhao, 2000) in the Aalenian–Bajocian, when the most important recoverable coal seams accumulated (Zhang et al., 1998). A series of NW–SE oriented fault-depression superimposed basins were pulled apart along the margin of the Qaidam Block by NE-trending extensional stress during the Early Jurassic (Wan, 2012). On this basis the Qaidam Basin represents an ideal target location to unveil the relationship between coal accumulation and the changes in palaeoclimates and provenance tectonic activity.

2 | GEOLOGICAL SETTING

The Qaidam Basin is one of the most important Jurassic coal-bearing basins in China. It covers an area of approximately 120,000 km² and is located in Qinghai Province (Figure 1a), with a latitude of...
approximately 30°N (Figure 1b). During the Jurassic Yanshanian period, the Qaidam Basin was a typical Mesozoic fault-depression superimposed basin. It entered the faulting stage during the Early Jurassic caused by north–south extension and developed a series of faulted basins in the eastern Dameigou area (Figure 1d; Yang et al., 2001). At the end of the Early Jurassic, uplift and compression commenced in the western part of the Qaidam Basin for the relative eastward movement of Tarim Block with respect to the Qaidam Block (Figure 1c; Zhao et al., 2000). The basin then entered the transitional period from fault to depression basin, which lasted until the end of the Bajocian (Liu et al., 2013; Yang et al., 2001). At this time, a regional lake transgression occurred and was initially centred on the Dameigou area, but subsequently, extended to the surrounding areas, including the Yuqia coalfield (Figure 1d). The Yuqia coalfield, located in the centre of the northern Qaidam Basin (Dai et al., 2003), is a narrow NE-trending coalfield with southern Qilian Mountain to the west and Lvliang Mountain to the south (Figure 1d). The basement comprises Proterozoic metamorphic rocks, Ordovician flysch, Carboniferous clastic rocks and limestone, and Caledonian intrusive rocks and volcanic rocks (Lu et al., 2007).

The coal-bearing strata of the Yuqia coalfield are Middle Jurassic in age and comprise the Dameigou Formation and the overlying Shimengou Formation (Figure 2). Several different stratigraphic divisions and correlation schemes for the Qaidam Basin have been proposed previously (Geology and Mineral Bureau of the Qinghai Province, 1991; Ritts & Biffi, 2001; Wu et al., 2011; Zhang et al., 1998). In this article, the updated stratigraphic scheme proposed by Zhang et al. (1998) is adopted. This scheme proves to be the most detailed and reliable one, as it is based on multi-disciplinary approaches, with refined subdivisions at stage-level, based on various evidence including lithostratigraphy, biostratigraphy (bivalves, plants, and spore-pollen) and chronostratigraphy (Wang, Mosbrugger, & Zhang, 2005). According to this scheme, the Dameigou Formation was dated to the Aalenian–Bajocian Stage, the Shimengou Formation was dated to Bathonian Stage (Figure 2).

### 3 | MATERIALS AND METHODS

The database for this study consists of 30 borehole cores and well logs undertaken during coal and shale gas exploration, 76 sandstone samples of the YQ-1 well, and identification data of sandstone slices from the Dameigou Formation in the Yuqia coalfield. The distribution of boreholes is shown in Figure 3. Lithofacies were described in cores...
including lithology, sedimentary structures, sand body geometries, and fossils, which were described and correlated in dip and strike cross-sections. Third-order sequences within the Dameigou Formation were recognized following criteria established by Catuneanu et al. (2009). Sequences within the Dameigou Formation were identified and correlated using borehole cores, well logs of gamma-ray and apparent resistivity. A series of analytical contour maps have been drawn in the third-order sequences using single-factor analysis and multifactor comprehensive mapping as proposed by Feng (2004). These lithofacies, sequence stratigraphic, and palaeogeographical characteristics were further related to the basin evolution and coal accumulation.

Sandstone samples were cut into slices and identified by the point-counting method under a microscope according to China national standards (SY/T5368-2003; SY/T 5368–2016), with more than 300 effective points of each sample. The classification of clastic rock components is in accordance with that of Dickinson (1985).

The mineral index of alteration (MIA) was applied to recover the evolution history of palaeoclimate during the Aalenian–Bajocian, which is a measure of unstable feldspars. It can be used to quantify the degree of weathering in the source area, and is not affected by sorting or abrasion (Nesbitt, Young, McLennan, & Keays, 1996; Rieu, Allen, Plötze, & Pettke, 2007). The Mineral Alteration Index is calculated as follows:

\[
\text{MIA} = \left[\frac{\text{quartz}}{\text{quartz} + \text{plagioclase} + K - \text{feldspar}}\right] \times 100, \text{using point-count modal proportions.}
\]

High MIA values (80–100) reflect a substantial loss of feldspar relative to quartz due to intense chemical weathering in humid and warm conditions, whereas low MIA values (50–70) are indicative of minimal weathering, and arid and/or cold condition (Roy & Roser, 2013). The TI (L/Q) reflects the tectonic activity of the sandstone detrital deposits (Cao, Li, & Wang, 2008). High lithic fragments content indicates strong tectonic activity, while low lithic fragments content indicates relatively stable tectonic activity (Cao, 2007).

4 | RESULTS

4.1 | Lithofacies types and characteristics

According to the colour, lithology and sedimentary structure of the sediments in the Dameigou Formation, four major lithological types and seven kinds of lithofacies are identified (Table 1). The characteristics, distribution, and interpretation of each lithofacies are described as follows.

4.1.1 | Conglomerate

Conglomerate comprises lithofacies Cg and is mainly distributed in the eastern part of the research area. This lithofacies is characterized by a cylindrical-shaped logging curve (Figure 4a) and composed of greyish-white, thick-bedded conglomerate, with gravelly clastic texture, upward-fining sequence, graded bedding, and scoured surface developed (Figure 5b,c). The gravel is more than 85% in content with a grain size range from 0.5 to 2 cm, sub-rounded to rounded, moderately sorted, and arranged with imbrication. The conglomerate comprises the gravel and the matrix with the composition of quartz, flint, and the sandy detritus, respectively, which is porous cementation with the calcareous cement. The Cg lithofacies represents most likely a
4.1.2 | Sandstone

Sandstone includes lithofacies Sp and Sw, which are widely distributed throughout the coalfield. Lithofacies Sp, with sandy clastic texture, middle/thick-bedded, upward-fining sequence, parallel bedding and scoured surface developed (Figure 5g), is greyish-white, medium-coarse grained sandstone. The detritus from lithofacies Sp, with a grain size range from 0.5 to 2 mm, is sub-rounded to rounded, well-sorted, whose composition is mainly quartz, followed by feldspar, lithic fragment, and a small amount of charcoal (Figure 5g,f). Lithofacies Sp is characterized by a bell-shaped or funnel-shaped logging curve (Figure 4b–d) and interpreted as a high-energy and oxidizing environment, such as the river or distributary channel. Lithofacies Sw consists of greyish-white fine-silt grained sandstone, is characterized by sandy clastic texture, thin-bedded, bell-shaped, or funnel-shaped logging curve (Figure 4), upward-fining sequence and wave-bedding (Figure 5h,j), and has abundant charcoal on the bedding surfaces of formation (Figure 5i). This lithofacies represents medium energy and weak oxidizing environment, such as the riverbank and shore-shallow lake (Table 1).

4.1.4 | Organic rock

Organic rock mainly comprises lithofacies C. This lithofacies is composed of black coal seam and is characterized by a cylindrical-shaped logging curve (Figure 4b–e) and thin-bedded, with plenty of plant fossils on the plane of formation. The lithofacies C is widely distributed throughout the study area and represents the low-energy and reducing peat swamp environment (Table 1).

4.2 | Depositional systems and sedimentary characteristics

Nine samples (sample number: M1–M9 from the bottom to the top) were selected to draw the probability graph of sandstones (S1–S3) in the Dameigou Formation based on the grain-size analysis (Figure 6).
The sedimentary grain-size characteristics of the sandstones are analysed as follows:

The probability graph of sample M1–M6 is characterized by ‘high slope-saltation-suspension’, which mainly consists of two parts: the saltation population and the suspension population (Figure 6). The saltation population is the main part of the sediment, with a content of more than 80%. Linear segment slopes of the saltation population are high and the detrital particles are well-sorted. However, the suspension population is rarely developed, and linear segment slopes are relatively low. Therefore, sample M1–M6 can be interpreted as point bar or channel bar sediments (Li, Zheng, Gong, Zhou, & Cheng, 2013; Yang, 1987). The probability graph of samples M7, M8, and M9 is each characterized by three-stage, with the saltation population as the main part (Figure 6). The detrital particles are well-sorted and the size is between 2.0 and 4.5 φ. The content of the suspension population and the rolling population are relatively low, which can be interpreted as sandbar deposits.

**Figure 4** Depositional systems of the Dameigou Formation in the Yuqia coalfield. (a) Braided fluvial; (b) abandoned channel; (c) meandering fluvial; (d) meandering fluvial; (e) lacustrine. Codes for lithofacies refer to Table 1. C, coal seam; Cg, graded bedding conglomerate facies; Den, Density; GR, Natural gamma-ray; Mh, horizontal bedding mudstone facies; Mm, massive bedding mudstone facies; Rt, Resistivity; Sp, parallel bedding sandstone facies; Sw, wavy bedding sandstone facies [Colour figure can be viewed at wileyonlinelibrary.com]

| Layer | Lithofacies | RT Code | Logfacies | Microfacies | Subfacies |
|-------|-------------|---------|-----------|-------------|-----------|
| (a)   | DENGR       | Y1      |           |             |           |
|       |             |         | Sw        | Zigzag      | Alluvial flat | Embankment |
|       |             |         | Cg        | Cylindrical | Braided river | River |
|       |             |         | Sw        | Zigzag      | Alluvial flat |           |
|       |             |         | Cg        | Cylindrical | Braided river |           |
|       |             |         | Cg        | Cylindrical | Braided river |           |
|       |             |         | Cg        | Cylindrical | Braided river |           |
|       |             |         | Sw        | Zigzag      | Alluvial flat | Embankment |

| Layer | Lithofacies | RT Code | Logfacies | Microfacies | Subfacies |
|-------|-------------|---------|-----------|-------------|-----------|
| (b)   | DENGR       | Y16     |           |             |           |
|       |             |         | C         |              | Peat swamp |
|       |             |         | Sw        | Zigzag      | Lakeside |
|       |             |         | C         |              | Peat swamp |
|       |             |         | Sw        | Bell shaped  | Lakeside |
|       |             |         | Sp        |              | Lakeside |
|       |             |         | C         | Zigzag      | Peat swamp |
|       |             |         | Sw        | Bell shaped  | Lakeside |
|       |             |         | Sp        |              | Abandoned channel |

| Layer | Lithofacies | RT Code | Logfacies | Microfacies | Subfacies |
|-------|-------------|---------|-----------|-------------|-----------|
| (c)   | DENGR       | Y11     |           |             |           |
|       |             |         | Mh        | Bell shaped | Floodplain |
|       |             |         | C         |              | Embankment |
|       |             |         | Mh        | Bell shaped | Natural levee |
|       |             |         | Sw        | Funnel-shaped | Shallow lake |
|       |             |         | Sp        |              | Embankment |
|       |             |         | Sw        | Funnel-shaped | Crevasse splay |

| Layer | Lithofacies | RT Code | Logfacies | Microfacies | Subfacies |
|-------|-------------|---------|-----------|-------------|-----------|
| (d)   | DENGR       | Y5      |           |             |           |
|       |             |         | C         | Funnel-shaped | Peat swamp |
|       |             |         | C         | Cylindrical | Lakeside |
|       |             |         | Sw        | Funnel-shaped | Lakeside |
|       |             |         | C         | Cylindrical | Lakeside |

The sedimentary grain-size characteristics of the sandstones are analysed as follows:

The probability graph of sample M1–M6 is characterized by ‘high slope-saltation-suspension’, which mainly consists of two parts: the saltation population and the suspension population (Figure 6). The saltation population is the main part of the sediment, with a content of more than 80%. Linear segment slopes of the saltation population are high and the detrital particles are well-sorted. However, the suspension population is rarely developed, and linear segment slopes are relatively low. Therefore, sample M1–M6 can be interpreted as point bar or channel bar sediments (Li, Zheng, Gong, Zhou, & Cheng, 2013; Yang, 1987). The probability graph of samples M7, M8, and M9 is each characterized by three-stage, with the salutation population as the main part (Figure 6). The detrital particles are well-sorted and the size is between 2.0 and 4.5 φ. The content of the suspension population and the rolling population are relatively low, which can be interpreted as sandbar deposits.
It can be seen from analyses above that the probability graph of the Dameigou Formation in the study area has evolved from two-stage to three-stage or even four-stage from bottom to top, reflecting the process of the hydrodynamic conditions from strong to weak. The sedimentation of the point bar or channel bar is converted into the sedimentation of the sandbar. In summary, it can be identified that the sandstones in the Dameigou Formation are fluvial and lacustrine sediments.
The parameter points of the sandstones (11 points) in the C-M diagram are mainly distributed in the PQ segment, QR segment, and RS segment which represents the fluvial sediments (Figure 7). The PQ, QR, and RS segments account for about 7, 50, and 21%, respectively. Another three points fall within the turbidity sedimentary range, which may be attributed to the rapid flow of rivers during the flood period, causing the resuspension of sediments. Overall, sandstones in the study area have a famous distribution pattern of the fluvial depositional system in the C-M diagrams (Passega, 1977; Passega & Byramjee, 1969).

Based on the comprehensive analyses of lithofacies, the logging phase, and the sandstone grain-size probability graph, it is believed that the Dameigou Formation mainly developed as a fluvial-lacustrine depositional system (Table 2).

### 4.3 Sequence-stratigraphic analysis

Based on the principle of the sequence interface identification proposed by Catuneanu et al. (2009), and sequence-stratigraphic framework suggested by Li et al. (2014), three sequence interfaces are recognized, including: (a) the regional unconformity surface, (b) the river undercutting surface, formed by forced lake regression, and its corresponding integration surface, and (c) surfaces that mark abrupt depositional facies shifts. The Dameigou Formation can be subdivided into two third-order sequences from the bottom to the top as Sequence 1 (SIII1) and Sequence 2 (SIII2). According to the Stratigraphic Chart of China (2018; Cohen, Finney, Gibbard, & Fan, 2013), the Dameigou Formation corresponds to the Aalenian–Bajocian stage of the Middle Jurassic age, ranging from 174.1 to 168.3 Ma, and lasts for 5.8 Ma. Assuming that the two sequences have similar duration, each sequence would last for ~2.9 Ma, which is within the range of 0.5–5 million years for a third-order sequence duration (Vail, Mitchum, & Thompson III, 1977). Systems tracts are interpreted based on stratal stacking patterns (Catuneanu, 2006), the key surfaces, the types of sequence boundaries, and the base-level change, including the lowstand systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST). In order to reveal the change characteristics of systems tracts and sedimentary facies in the Dameigou Formation, three cross-sections are drawn along the dip and strike directions through the basin (Figures 8-10). The sequence-stratigraphic characteristics are described as outlined below.

The lower sequence boundary of SIII1 is a regional unconformity separating the Middle Jurassic Dameigou Formation and the underlying Upper Ordovician strata. LST and TST can be recognized in this sequence based on the stacking patterns of the component stratigraphy. The LST is locally developed and distributed on the east and west sides of the study area. It comprises coarse sandstone or gravel coarse sandstone sediments, representing the channel lag, braided river or channel bar sedimentation. The thickness of LST sediments changes...
significantly in its lateral extent. The sediment supply rate is enormous, and the basin is in the over-compensation stage of filling during this period. The TST is widely distributed in the study area and mainly composed of coal seams, carbonaceous mudstones, fine sandstones, and siltstones. It is relatively stable in the lateral direction and has a thinning trend from north-west to south-east. The basin is in the equilibrium compensation stage during this period, while the HST is locally developed in the study area and comprises mudstones developed in the shallow lake. The coal seam #6, with a thickness of 1.37–11.7 m, mainly developed in the TST of SIII2 (Figures 8-10).

4.4 Lithofacies palaeogeography and distribution characteristics of coal seams

To summarize the lithofacies and palaeogeography of the Dameigou Formation, a variety of maps have been produced in the sequence-stratigraphic framework based on the borehole data, that include relatively complete stratal successions in the study area. The palaeogeographical reconstructions are based on the third-order sequences presented above, with palaeogeographical maps for each system tract mainly based on the coal-seam isopach and multifactor comprehensive mapping method, synthesizing the
Previous works of palaeocurrent (Ritts, Hanson, Zinniker, & Moldowan, 1999; Zhao et al., 2000) and palaeogeography (Li et al., 2014) have contributed to our understanding of the stratigraphic sequence framework of the Middle Jurassic in Yuqia coalfield. The sedimentary boundary of the LST of SIII1 recovered by the borehole is shown in Figure 11a. The basement to the south of fault (F1) is relatively uplifted without deposition, while north of the fault it is characterized by a lowstand systems tract (Hunt & Tucker, 1992).
is relatively subsiding, which is the sedimentary centre of the basin. At the same time, the Lvliangshan palaeo-uplift developed near the NW-SE trend in the southern part of the study area. Under the control of fault F1, the sedimentary interface is high in the west and low in the east, with a fluvial palaeogeographic unit developed from west to east. After the intersection of the river and F1 on the eastern edge of the study area, the river turns to a south-east direction, and the alluvial lake is formed on the bank side of the river near boreholes Y4 and Y5. During this deposition period, the supply rate of terrigenous clastic sediments is greater than the generation rate of accommodation, and the basin is in the over-compensation stage. The main sediments in the study area are river glutenite, and the rivers are frequently migrated, with swamps rarely developed.

During the TST of SIII1, the sedimentary interface is relatively flat because of the filling effect in the LST. As the rising rate of the baselevel increased, the supply of terrigenous clastic sediments is small, and the sedimentary water flows over the palaeo-uplift (Figure 11b). The sediments mainly consist of greyish-black mudstone, siltstone, and coal. At this time, the sediment supply rate is equal to the increasing rate of the accommodation, and the basin is in the equilibrium compensation stage. Because of the relatively slow subsidence rate of the basement, the influence of tectonic activity near the palaeo-uplift is relatively small. The surface area of the sedimentary water increased, and the rising rate of baselevel is relatively slow, with the vegetation flourishing. This is conducive to the accumulation and preservation of peat, representing a good place for coal accumulation.

During the TST of SIII2, the sedimentary water flows over the lower plate of fault F1 and the palaeogeographic unit of lake swamp is widely developed in the study area (Figure 11d). Owing to the filling effect of LST, the sedimentary interface is relatively flat and the basin is in the equilibrium compensation stage. At the same time, the vegetation flourishes and the peat production rate increases. The balance between the increasing rate of accommodation and the peat production rate can be achieved in a long time, which is conducive to the development of a coal seam.

4.5 | Palaeoclimate and provenance tectonic activities

The identification results of sandstone thin sections from the borehole YQ-1 in the study area are shown in Figure 12. The content of
The sandstone clastic components vary from 85 to 99% (x̄ = 93%) in the Dameigou Formation. The sandstone clastic components are mainly composed of quartz (Q), feldspar (F), and lithic fragments (L) in the study area. The quartz fragments mainly include monocrystalline quartz, polycrystalline quartz, and chert (Figure 13), and the content varies from 61 to 84% (x̄ = 73%). In the stratigraphic direction, the quartz content is characterized by rapidly increasing from bottom to top in the S1, while tending to be stable in the S2, and increasing first and then decreasing from bottom to top in the S3, with the average value of 65, 71, and 77%, respectively (Figure 12). The feldspar fragments mainly comprise potassium feldspar and plagioclase (Figure 13), and the content varies from 3 to 12% (x̄ = 7%). The feldspar content is characterized by rapidly decreasing in the S1, then increasing from the bottom to top in the S2 and S3, with the average value of 6, 7, and 8%, respectively (Figure 12). Lithic fragments include magmatic lithics (the interaction between quartz and feldspar), metamorphic quartz limestones, mica schist lithics, and slate lithic (Figure 13), and the content varies from 8 to 18% (x̄ = 13%). From bottom to top the lithic fragment content presents a gradually decreasing trend in the S1, a gradually decreasing trend in the S2, and tends to be stable in the S3, with average values of 16, 15, and 10%, respectively (Figure 12).

MIA values vary from 86.1–96.2 (x̄ = 91.1) in the Dameigou Formation. In the vertical direction, the average MIA value of the S1–S3 are 92.1, 91.3, and 90.4, respectively. Overall, MIA values present three apparent fluctuations in the Dameigou Formation. The first one occurs in the S1 where values increases from 88.2 to 93.8, while the second appears in the upper part of S2 and is characterized by a rapid decrease from 91.8 to 87.5 and then increasing till 96.2. The third fluctuation occurs in the lower part of S3 and is characterized by a rapid decreasing from 96.2 to 88.4 and then increasing from 88.4 to 93.2 and (Figure 12). Tectonic Index (TI) values range from 0.10 to 0.30 in the Dameigou Formation, with an average of 0.18. The average TI
values of the S1-S3 are 0.24, 0.20, and 0.13, respectively. There is a gradual decrease from 0.30 to 0.17 in the S1 while a significant fluctuation arises from the upper part of S2 to the lower part of S3, which decreases from 0.22 to 0.14. After that, the TI value is basically stable range from 0.10 to 0.15 (Figure 12).

5 | DISCUSSION

5.1 | Sequence stratigraphy and palaeogrography

Based on the analysis of the key bounding surfaces and sequence boundaries, the Dameigou Formation in the Yuqia coalfield was subdivided into one third-order sequence by Li et al. (2014). However, in this study, we divide the Dameigou Formation into two third-order sequences. According to the Stratigraphic Chart of China (2018) (Cohen et al., 2013), the Dameigou Formation lasts for 5.8 Ma, which exceeds the range of 0.5–5 million years for a third-order sequence duration (Vail et al., 1977). This is in agreement with our finding of dividing the Dameigou Formation into two third-order sequences. In the palaeogeographic map of the Dameigou Formation, five palaeogeographic units (including alluvial fan-braided fluvial plain, upper delta plain, lower delta plain, subaqueous delta, and shore-shallow lake) and three source areas (southeastern side, northwestern side, and eastern side) were recognized by Li et al. (2014). However, the sandstone grain-size probability graph in this study shows that the Dameigou Formation mainly developed as a fluvial-lacustrine depositional system. And according to the NW-trending of the Qaidam Basin and previous works on palaeocurrent (Ritts et al., 1999; Zhao et al., 2000), we
suggest that the major source area is more likely located in the Northwestern side of the basin.

5.2 Provenance tectonic activity analysis under the sequence stratigraphy framework

From the LST of SIII1 to the LST of SIII2, TI values are relatively high and the sandstone samples comprise a abundant and disorderly distributed debris. Many metamorphic quartzites and mica quartz schist lithics can be seen in sandstones under cross-polarized light, with a small amount of slate and magma lithics (Figure 14③,⑧). However, TI values are low and tend to be stable in the TST of SIII2, with the structure maturity and component maturity of the sandstone samples increased. Sandstones mainly composed of quartz and feldspar (Figure 14⑪,⑯), with a small amount of detritus. This is consistent with the decreasing trend of detritus content from the Lower Member to the Upper Member of Dameigou Formation in the Hongshan sag of the Qaidam Basin (Feng et al., 2017). High TI values may indicate that tectonic activity in the provenance area is strong, which corresponds to the faulting stage of the basin. In contrast, low TI values may represent that the provenance tectonic activity tend to be stable, which corresponds to the depression stage of the basin. Furthermore, Yu et al. (2017) also shows that the northern Qaidam Basin was in the rifting phase during the earliest part of the Middle Jurassic, and then developed into an extensional basins since the middle stage of the Middle Jurassic that was sustained until the end of the Jurassic. Therefore, a curve showing the intensity of tectonic activity is recovered inferred from TI values (Figures 15 and 16).

5.3 Palaeoclimates analysis under the sequence stratigraphy framework

In the Qaidam Basin, the vegetation during the Aalenian-Bajocian stages is represented by the exceptionally abundant fern families

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**FIGURE 14** Sandstone sampling positions and macro-microscopic characteristics. The core diameter from YQ-1 borehole is 6 cm; ① sampling position of S1; ② poorly sorted and rounded, normally graded; ③ erosional surface; ④ a significant amount of lithic fragments; ⑤ sampling position of S2; ⑥ moderately sorted and rounded, normally graded; ⑦ the main components are quartz and feldspar, with a small amount of mica; ⑧ large number of lithic fragments; ⑨ sampling position of the bottom of S3; ⑩ moderately sorted and rounded, parallel bedding developed; ⑪ main components are quartz, feldspar and a small amount of mica; ⑫ an amount of feldspar and a small number of lithic fragments; ⑬ sampling position of the top of S3; ⑭ wavy bedding developed; ⑮ main components are quartz, feldspar and a small amount of charcoal; ⑯ abundant feldspars [Colour figure can be viewed at wileyonlinelibrary.com]
Cyatheaceae and Dicksoniaceae, and Cycadophyte–Ginkgophyte gymnosperms, indicating a humid and warm climate (Wang et al., 2005). Considering the greenhouse climate in the Jurassic (Donnadieu et al., 2011), high MIA values in the study area reflect a humid and warm climates, while low MIA values indicate a dry and hot climates.

From the LST of SII1 to LST of SII2, except for a gradual increase with a small magnitude in the LST of SII1, MIA values present stable conditions. This suggests that climate experienced no significant fluctuations during this period. In the TST of SII2, MIA values fluctuate markedly and with large magnitudes, which indicates frequently fluctuating climatic conditions. Based on the MIA values, a climate model of the Aalenian–Bajocian stage in the Qaidam Basin is suggested, including an evolution from dry-hot climate to humid-warm climate in the Aalenian–Early Bajocian stage, a climate cycle from dry-hot to humid-warm then return to dry-hot in the Middle–Late Bajocian stage (Figures 15 and 16). This is consistent with the climate change trend of the coal seam #7 and #6 based on organic carbon isotopes in the Qaidam Basin (Lu et al., 2016). Humid and warm climates are generally correlated with the rising of sea-level while the dry and hot climate corresponding to the sea-level falls of JBj2 and JBj4 in the short-term sea-level curve revised by Haq (2018).

5.4 Coal accumulation linked to the changes in palaeoclimate and provenance tectonic activity

Coal accumulation based on sequence-stratigraphic analysis has been broadly used (Bohacs & Suter, 1997; Diessel et al., 2000; Holz et al., 2002; Li et al., 2018; Xu et al., 2020). The peat-forming environments were also discussed in sequence-stratigraphic intervals (Petersen, Lindström, Therkelsen, & Pedersen, 2013). Previous works can be summarized as ‘a coal seam would develop well when the increasing rate of accommodation kept balance with the production rate of peat, and the destruction of the balance will terminate the coal accumulation’ (e.g., Li et al., 2014, 2018; Xu et al., 2020). However, there are few studies on the quantitative analysis of palaeoclimate and provenance tectonic activity, and how they control
accommodation creation rates and sediment supply rates. Furthermore, most of the researches mainly focus on a single faulted basin or a depression basin (e.g., Wang et al., 2019; Xu et al., 2020), lacking the research on coal-accumulating models in a fault-depression superimposed basin. Based on the previous analysis of sequence stratigraphy, palaeogeography, palaeoclimate changes, and tectonic activity, two different coal-accumulation models are summarized in Figures 15 and 16, respectively. In the context of a fault-depression superimposed terrestrial basin with strong tectonic activity, coal accumulation under the sequence-stratigraphic framework can be summarized in the following six stages:

(a) Before the rise of baselevel, a steep sedimentary interface is formed and the river is eroded due to the strong tectonic activity. (b) The baselevel started to rise, causing a low rate of accommodation creation, which was less than the rate of sediment supply. The fluvial channel began to fill the incised valleys, forming relatively continuous sand bodies, and the accommodation was primarily occupied by terrigenous clastics. (c) During the early TST, the valleys gradually flooded and reduced the fluvial depositional systems. The rate of generation of new accommodation increased and almost coincided with the rate of the sedimentary rock supply. The basin was mainly shore-shallow lakes. The coal-forming vegetation flourished between the fluvial channels and contributed to the peat accumulation during this period. The balance between the rate of accommodation generation and peat production can be reached over a long time because of the slowdown of the accommodation generation rate caused by the relative weakening of tectonic activity in the early TST (Figure 15), which led to the continuous coal seam #7. (d) The HST started from the baselevel reaching the MFS. The rate of base-level rise was higher than the rate of peat accumulation, depositing a fine-grained succession overlying coal seams. Accommodation increased due to the strengthening of tectonic activity, and the coal-forming plants and peats were drowned. Thus, coal accumulation terminated. (e) After the rate of base-level rise reached its maximum value, it began to fall. The terrigenous clastics revived as the accommodation space decreased and the shoreline translated to a basinward direction. The basin was primarily occupied by fluvial environments; incised valleys also developed during this period and scoured the underlying

**FIGURE 16** Schematic diagram showing the accumulation progress of the coal seam #6 of the Middle Jurassic in the Yuqia coalfield. dec., decrease; inc., increase [Colour figure can be viewed at wileyonlinelibrary.com]
successions at the edge of the basin. Meanwhile, there is an upward-finishing sequence deposited at the centre of the basin. (f) The basin entered on the normal LST of SIII2 when the baselevel starts to rise again. As the rising rate of the baselevel was less than the sediment supply rate, the fluvial channels began to fill the incised valleys, forming relatively continuous sand bodies, and the accommodation was primarily occupied by terrigenous clastics. The relatively flat depositional interface formed in this period was an important prerequisite for the basin swamping.

As a whole, during the faulting stage, the occurrence and termination of coal seams were mainly controlled by tectonic activity. In the fault-depression area (Y6, Y10, and Y13), tectonic activity was strong and the basement subsidence rate the fastest, where it was difficult to reach a balance between the rate of accommodation creation and the peat accumulation for a long time because of the small catchment area and the fast-rising baselevel. Therefore, coal seam #7 that developed in this area was multi-gangue and bifurcates in its lateral extent. However, the basement subsidence rate was slow in the palaeo-uplift (Y3 and Y8), and the area of the sedimentary water gradually expanded as the lake level passed through the palaeo-uplift. This resulted in a decrease in the rate of base-level rise and accommodation creation in the palaeo-uplift. Thus, the balance between the rate of peat production and accommodation creation can be sustained for a long time. Therefore, coal seam #7 developed in the palaeo-uplift was large in thickness and less in gangue.

During the depression stage with stable tectonic activity, the coal accumulation under the sequence-stratigraphic framework can be summarized into the following four periods. (g) During the early TST (Figure 16), the valleys gradually flooded and reduced the fluvial depositional systems. The rate of new accommodation generation increased and almost coincided with the rate of the sedimentary rock supply. However, the climate experienced a short dry and hot phase during this period, which was not conducive to the growth of peat-forming vegetation and peat accumulation, resulting in an absence of coal seam formation. Therefore, a fine-grained succession was deposited which belongs to the lacustrine sedimentary system. (h) During the middle TST, as the humidity and warmth of the climate and the continuous rise of the baselevel, peat-forming vegetation flourished, forming a large area of exposed and weak-overlying water environment conducive to peat accumulation at the flat sedimentary interface formed previously. Therefore, the balance between the rate of peat production and accommodation creation can be reached which led to the formation of continuous coal seam #6. (i) During the late TST, the climate also experienced a short dry and hot process at the roof of the coal seam #6. As the climate became drier and hotter, the vegetation in the source area decreased and river erosion was enhanced, which result in the resurrection of the terrigenous system and termination of coal accumulation. A fine-grained succession was deposited overlying coal seams. (j) The HST started when the climate became warm and humid again and the baselevel reached the MFS. The rate of base-level rise was higher than the rate of peat accumulation, depositing lacustrine siltstones and mudstones.

Generally, during the depression stage, the difference in subsidence rate of the basement was reduced, and the change of climate affected the change of the baselevel and the growth of coal-forming plants, thus controlling the development of the coal seam. Due to the relatively flat depositional interface formed in this period, coal seam #6 in the study area was less in gangue and good in continuity.

6 | CONCLUSIONS

1. We recognized six kinds of lithofacies and two sedimentary systems that divide the Dameigou Formation into two third-order sequences by regional unconformity surface, forced regression surface and their correlative conformity surface, and the abrupt shift surface of depositional facies. Results demonstrate that the main #7 and #6 coal seams were deposited in lake swamp environment during periods of lake transgression.

2. The TI indicates that the source area was in strong tectonic activity stage from the SIII1 to the LST of SIII2 and then gradually stabilized. MIA results reveals that the climate evolution of SIII1 was from dry-hot to humid-warm and there is a climate cycle from dry-hot to humid-warm then a return to dry-hot in the SIII2.

3. During the faulting stage, the occurrence and termination of coal accumulation was in response to the weakening and strengthening period of tectonic activity respectively, while it response to the humid-warm and dry-hot climate during the depression stage.

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