Research Article

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Sequence stratigraphy and coal accumulation model of the Taiyuan Formation in the Tashan Mine, Datong Basin, China

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Abstract: Datong Basin is a platform uplift formed in the Cenozoic era and has a significant coal-bearing geological unit in China. Tashan Mine is located in the middle-eastern part of the Datong Basin, the coal resources of the Taiyuan Formation are abundant, and the research value is enormous. Of the coal resources, coal seams 3–5 and 8 are the main. The lack of research in sequence stratigraphy, coal-forming environment, coal-accumulating model limits the layout efficiency of working face and the exploration and development efficiency of coal measures associated resources. This study used sedimentary and sequence stratigraphy and calculated and measured field drilling data to investigate the sequence stratigraphic characteristics, paleogeographic pattern, and coal accumulation model of the Taiyuan Formation. The sequence boundary and system tract boundary were identified, and the Taiyuan Formation was divided into four third-order sequences. The paleogeographic pattern was reconstructed with the third-order sequence as a unit by applying the single-factor analysis and multifactor comprehensive mapping. Additionally, the distribution characteristics of the main coal seams were clarified, and the corresponding coal accumulation model was reconstructed. The results exhibit that the sedimentary facies transformed from carbonate platform–tidal flat–lagoon–shallow water delta facies to shallow water delta facies from SQ1 to SQ2, coal seam 8 formed in interdistributary bay microfacies and peat swamp microfacies in SQ1. Transgression further expanded in SQ3, and the sedimentary facies were still dominated by the shallow water delta facies. Coal seams 3–5 are formed in distributary channel microfacies, which consist of interdistributary bay microfacies and peat swamp microfacies. The paleogeographic pattern was still dominated by shallow water delta in SQ4, in which interdistributary depressions and peat swamp microfacies widely developed. The thickness of coal seams 3–5 is in the range of 2.40–25.90 m, in which the northwestern study area is characterized by moderate water depth and sufficient fine sediment, and the widely developed distributary bay and peat swamp deposited a thick coal seam. The thickness of coal seam 8 is in the range of 0.5–10.5 m, and the thickness is stable (mostly thicker than 6 m) controlled by the widely developed lagoon, mud flat, and peat swamp microfacies and reduction water environment.

Keywords: sequence stratigraphy, coal accumulation model, Taiyuan Formation, Tashan mine

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1 Introduction

Datong Basin is one of the key areas of coal resource development in China, and the previous exploration practice and mining experience have proven that the Carboniferous–Permian coal resources are abundant [1–3]. Additionally, the exploration of coalbed methane and shale gas resources is being actively carried out in recent years. Tashan Minefield is located in the middle-eastern part of the Datong Basin, and it is a dual-period coalfield of the Jurassic and Carboniferous–Permian [4,5]. Four reflective layers have been identified in the Taiyuan Formation, and the Taiyuan Formation is divided into the Jinci, Maoergou, and Qiligou sections from bottom to top. Due to the exhaustion of the Jurassic coal resources, the role of the Carboniferous–Permian coal resources within the Datong Basin is being greater [6–8]. The understanding of the occurrence, sedimentary evolution, and coal accumulation characteristics of coal seams is the basis of coal exploration and development. Taiyuan Formation consists of ten coal seams, with an average coal thickness of 17 m and a coal-bearing coefficient of 20% [8].

Gong [6] suggested that there are two evolutionary stages in the sedimentary period of the Taiyuan Formation, the delta sedimentary evolution stage in the early middle period and the river sedimentary evolution stage in the late period. Yang [7] demonstrated that the Taiyuan Formation is dominated by marine–continental transition facies deposits, and the sedimentary thickness tends to thin from north to south. Dou et al. [4,9] investigated the coal-forming and sedimentary environment of coal seam 3 of the Taiyuan Formation and suggested that there are three distinct sedimentary cycles in the vertical direction. During the formation of coal seam 3, the characteristics exhibit a transformation process from marine to continental.

Although predecessors have done a lot of fruitful research work, several problems still need to be solved urgently of the Taiyuan Formation in the Tashan Mine: (1) the recognition of sequence stratigraphy is mostly focused on the Datong Basin, whereas the investigation of the Tashan Mine is rare; (2) the research of the coal-forming environment and coal accumulation model is mostly aimed at a single coal seam, and thus, the comprehensive recognition of the whole Taiyuan Formation requires further work; and (3) most investigations are based on single drilling or stratigraphy profiles, and additional basic data are needed to ensure the accuracy of the results. Therefore, this investigation aims to recognize the sequence stratigraphic characteristics and coal accumulation model of the coal-bearing rocks, classify the third-order sequence, and reconstruct the paleogeographic environment. The Taiyuan Formation of the Tashan Mine was taken as the research subject, and the measured profiles of the Benxi–Shanxi Formation in the Liangtoucun section and 55 drillings are taken as the research basis. Results from this study reveal the characteristics of sedimentary environment and sequence stratigraphic, coal accumulation model, and spatial characteristics of coal seams 3–5 and 8 in the Tashan Mine, which provides a specific reference for coal seam mining and construction and the development of unconventional natural gas resources in coal measures.

2 Geological background

Tashan Mine is in the middle-eastern Datong Basin, which is located on the southern side of the Mongolia–Yinshan uplift structural belt in northern China [10–12]. Tectonic movements frequently occur after the sedimentation of the Taiyuan Formation [13]. The basin uplifted during the upper Shihezi period of the Late Permian, and the sedimentary range began to decrease. The basin was finally closed by the end of the Permian. Influenced by multistage tectonic movements, the distribution of the Carboniferous–Permian residual coal-bearing basins is generally in the direction of northeast (NE)–southwest (SW) (Figure 1). Tashan Mine is also distributed along the direction of NE–SW, and the general shape is characterized by wide in the SW and narrow in the NE. The eastern boundary is a large north–south reverse fault; Tongxin coalfield, Majiliang coalfield, and Dongzhouyao coalfield are the northern adjacent; Panjiayao coalfield is the western adjacent; and the Madaotou coalfield and Lucaogou coalfield are the southern adjacent (Figure 1). The Taiyuan Formation is underlain by the mudstone of the Benxi Formation and overlying by the K3 sandstone of the Shanxi Formation and all of which are in integrated contact. The Taiyuan Formation in the study area is rich in coal resources, especially in the Jinci and Maoergou sections. It consists of ten sets of coal seams (coal seams 1–10) of which coal seams 3–5 and 8 are the main.

3 Research methods

On the basis of the geological background of the Tashan Mine, the theory of sedimentology and sequence stratigraphy is applied to analyze drilling and logging data. Starting with a typical drilling, the different lithofacies characteristics and the corresponding sedimentary facies are summarized. Then, sequence boundaries and system tract boundaries are identified by drilling comparison. The single-factor analysis [10,11] is carried out by using the thickness of limestone, sandstone, sand content, and coal seams of different sequences, and the paleoenvironment can be reconstructed by the results of the above factors. Finally, sedimentary evolution and coal accumulation model of the Taiyuan Formation are discussed.

4 Lithofacies characteristics and sedimentary interpretation

The coal measures of the Taiyuan Formation are mainly composed of sandstone, siltstone, mudstone, and coal seam (Figures 2 and 3). According to the characteristics of color, component, sedimentary structure, and paleontology of the drilling cores in drilling A24, the lithology types are classified, and the sedimentary environments are interpreted. The seven sedimentary microfacies are identified as follows (Table 1): distributary bay, distributary channel, peat swamp, lagoon, mud flat, mixed flat, and barrier bar.

5 Analysis of sequence stratigraphy

In the process of establishing the sequence cartographic framework of the Taiyuan Formation in the Tashan Mine, the concept of sequence, sequence and system tract boundaries adopt Vail's viewpoint to identify the key stratum boundaries.

5.1 Recognition of sequence boundary and system tract boundary

5.1.1 Recognition of second-order sequence boundary

5.1.1.1 Erosion surface of the incised valley

Sandy conglomerate bodies directly cover the basement or develop on fine-grained sedimentary rocks, often representing a regional erosion surface, which represents the sequence boundary formed by the slope of the erosion base level [14,15].

The boundary between Taiyuan Formation and the underlying Benxi Formation is a regional conversion surface of sedimentary systems (the sequence boundary of the bottom of the Jinci sandstone [K1]; Figure 3c). Under the conversion surface, it is mainly composed of a carbonate tidal flat-barrier bar – lagoon sediment system, with a thick layer dark mudstone and carbonaceous mudstone (fossil plants developed) developed. However, it gradually evolved from marine facies to transitional facies above the conversion surface, the lithology is mainly moderate coarse sandstone, and the bottom is usually fine conglomerate or conglomerate-bearing sandstone. The logging characteristics are as follows: the apparent resistivity curve amplitude, acoustic time difference curve amplitude, and natural gamma curve amplitude are all low, in which the natural gamma curve is an inverted box shape, whereas the density curve amplitude is high, and it has an erosion effect on the underlying strata, causing erosion to the Benxi Formation.

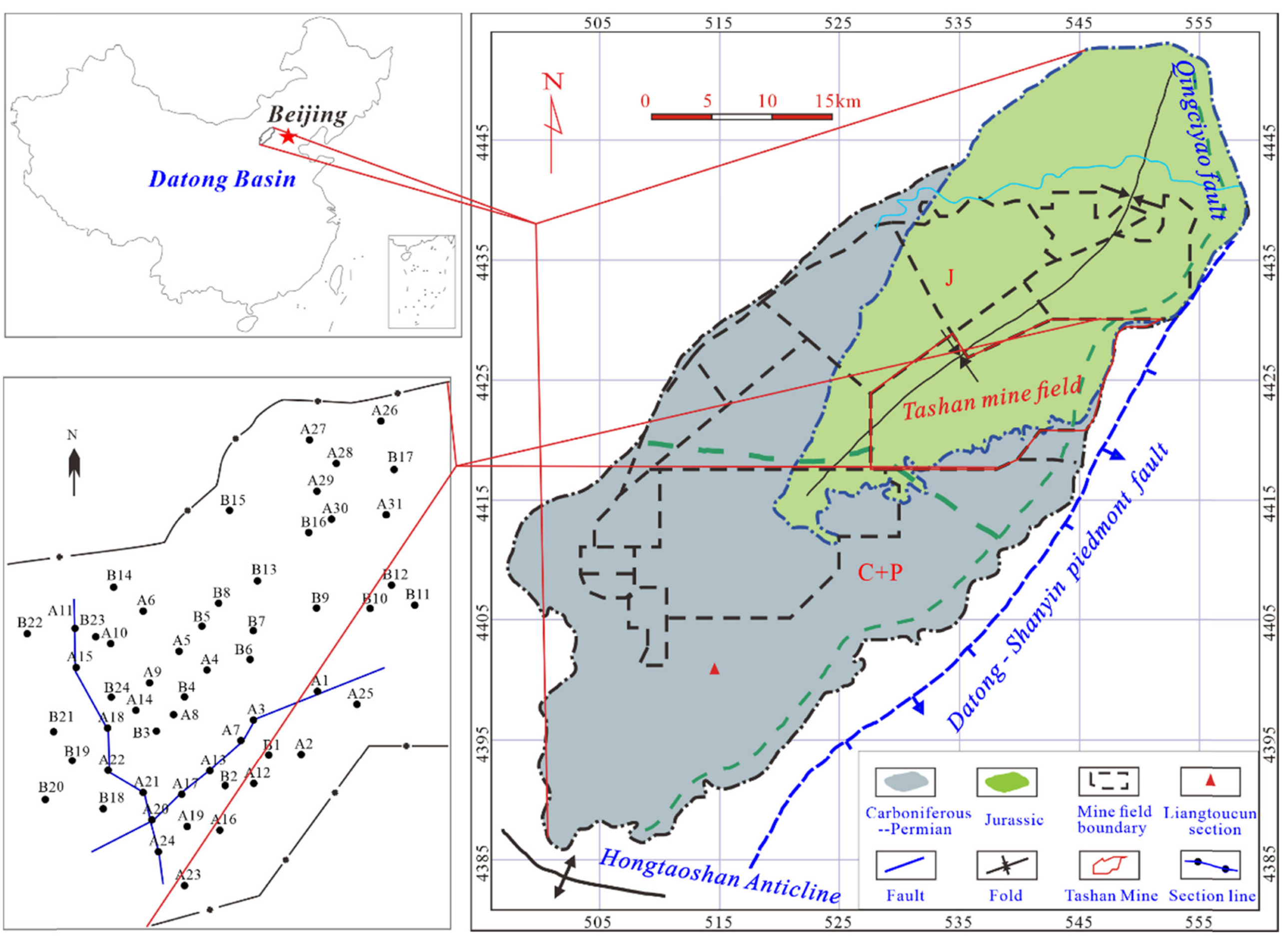

Figure 1: Location of the study area and drillings distribution.

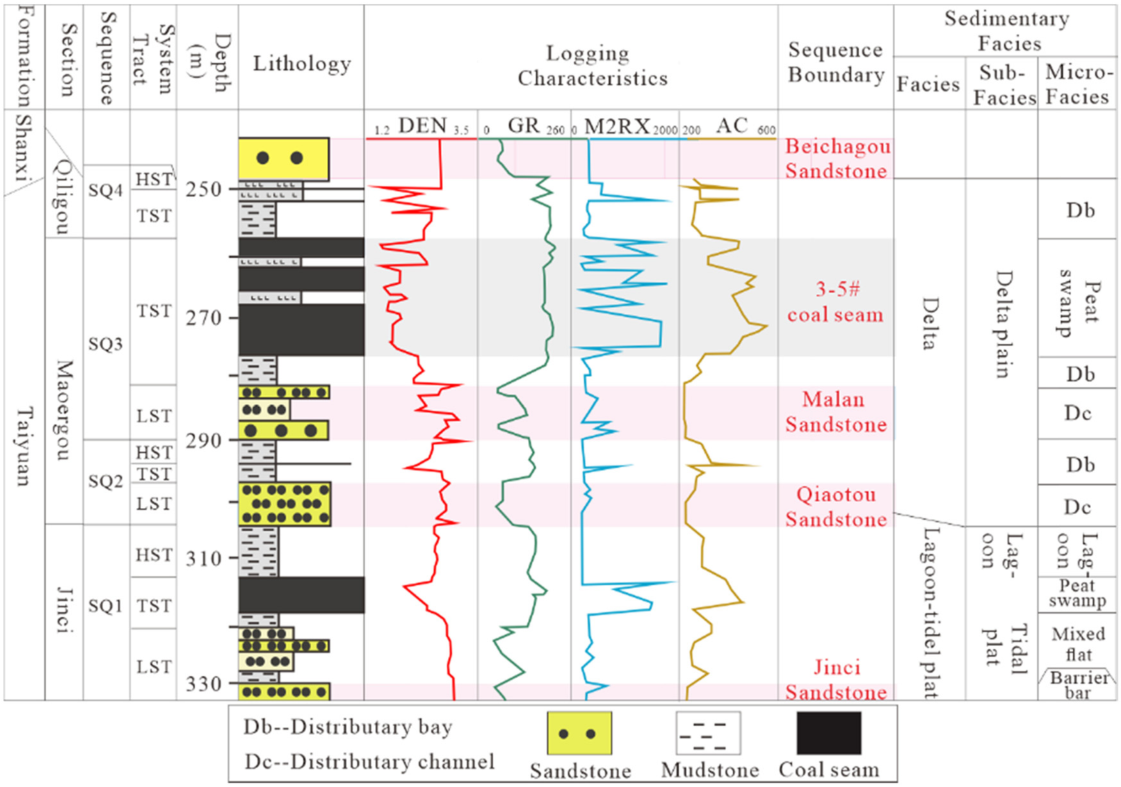

Figure 2: Logging response characteristics of sequence boundary of the Taiyuan Formation in well A24.

5.1.1.2 Regional unconformity

This boundary represents the depositional hiatus, and the lithological mutation, the depression of the basement, and the unconformity of sedimentary caprock often occur [16,17].

The boundary between Taiyuan Formation and the Shanxi Formation belongs to a sedimentary discontinuity (the bottom surface of the Beichagou sandstone [K3]). The logging characteristics are similar to those of K1; the apparent resistivity curve amplitude, acoustic time difference curve amplitude, and natural gamma curve amplitude are low, in which the natural gamma curve is an inverted box shape, whereas the density curve amplitude is high. Additionally, the development of incised valley results in the partial absence of the upper strata of the Taiyuan Formation.

5.1.2 Recognition of system tract boundary

5.1.2.1 First flooding surface

The sea water first crosses the edge of the shelf, which is the physical boundary between the lowstand system tract (LST) and the transgressive system tract (TST) [18,19]. The concrete manifestation is enlargement of the sedimentary range and the deepening of the sedimentary water. The first flooding surface is the bottom surface of mudstone or siltstone with medium and thick layers in the study area, under which the incised channel sandy conglomerate is developed.

5.1.2.2 Maximum flooding surface

The boundary formed of the maximum transgression in the sequence, which is the physical boundary between the TST and the highstand system tract (HST) [18,19]. Under the boundary, the lithology shows an upward fining sequence, and the bottom of the last layer can be identified as the maximum flooding surface with the finest layer thickness.

5.1.3 Classification of third-order sequence boundary

The third-order sequence boundary is subordinate to a further subdivision of the second-order boundary. In this study, the sequence boundaries developed in the Taiyuan

Figure 3: Characteristics of hand specimens from coal measures of the Taiyuan Formation: (a) gray mudstone – siltstone in the Maoergou section, (b) Malan sandstone – fine-grained lithic quartz sandstone, (c) Jinci sandstone – fine-grained quartz sandstone, and (d) Qiaotou sandstone – coarse-grained lithic quartz sandstone.

Table 1: Lithologic characteristics and sedimentary facies of the Taiyuan Formation

Lithofacies	Rock characteristics	Sedimentary structure	Sedimentary environment
Dark mudstone and siltstone	Thin layer, gray, gray–white, better sorting, containing a little plant fossil	Horizontal bedding	Distributary bay
Lithic quartz sandstone	Thick layer, gray–white, light gray, medium sorting, medium grinding	Tabular cross bedding, parallel bedding	Distributary channel
Black mudstone, carbonaceous mudstone, and coal	Black	Massive bedding	Peat swamp
Silty mudstone and argillaceous siltstone	Thin layer, gray, dark gray, containing brachiopod fossils, and plant fossils	Horizontal bedding, wavy bedding, and biodisturbance structure	Lagoon
Sandy mudstone and silty mudstone	Thick layer, gray, dark gray, containing plant root fossils	Horizontal bedding, lenticular bedding, and biodisturbance structure	Mud flat
Sandstone–mudstone interbedding	Thin layer, gray	Interbedding structure	Mixed flat
Coarse-grained quartz sandstone	Thick layer, gray–white, better sorting, better grinding	Tabular cross bedding, wavy cross bedding	Barrier bar

Formation belong to the exposed surface on land or its underwater counterpart, including the paleosol surface, the paleoweathering surface, the transformation surface of the sedimentary system, and the erosion surface of the river.

5.1.3.1 The sequence boundary of the bottom sandstone in the bottom of the Maoergou section

For convenience of description, it is abbreviated as the Qiaotou sandstone (Figure 3d), and it is the erosion surface of the river. Its logging characteristics are similar to K1, the amplitude of the apparent resistivity curve, while the amplitude of the acoustic time difference curve and natural gamma curve is all low, in which the natural gamma curve is box shaped, whereas the amplitude of the density curve is high (Figure 2).

5.1.3.2 The sequence boundary of the bottom sandstone in the middle Maoergou section

For convenience of description, it is abbreviated as the Malan sandstone (Figure 3b), and it is the erosion surface of the river. The logging characteristics are similar to those of the Qiaotou sandstone, which has washed action on the underlying strata (Figure 2).

5.1.3.3 Sequence boundary of the top surface of coal seams 3–5

The maximum flooding surface is the coal seam formed during the maximum transgression in the North China Basin. This is one of the main coal seams with the largest thickness and complex structure. Logging characteristics show a multipeak shape with a low upper and a high middle, and the natural gamma-ray curve shows a wide polydentate shape. It is the thickest coal seam of the Taiyuan Formation in the study area (Figure 2).

Qiaotou sandstone, Malan sandstone, and coal seams 3–5 are widely developed in the study area, with a stable thickness, good ductility, and obvious characteristics, which are the high-quality marker beds and compare beds (Figure 2).

5.1.4 The establishment of the sequence stratum framework

The third-order sequence boundary developed in the Taiyuan Formation is identified based on previous research [20–22]

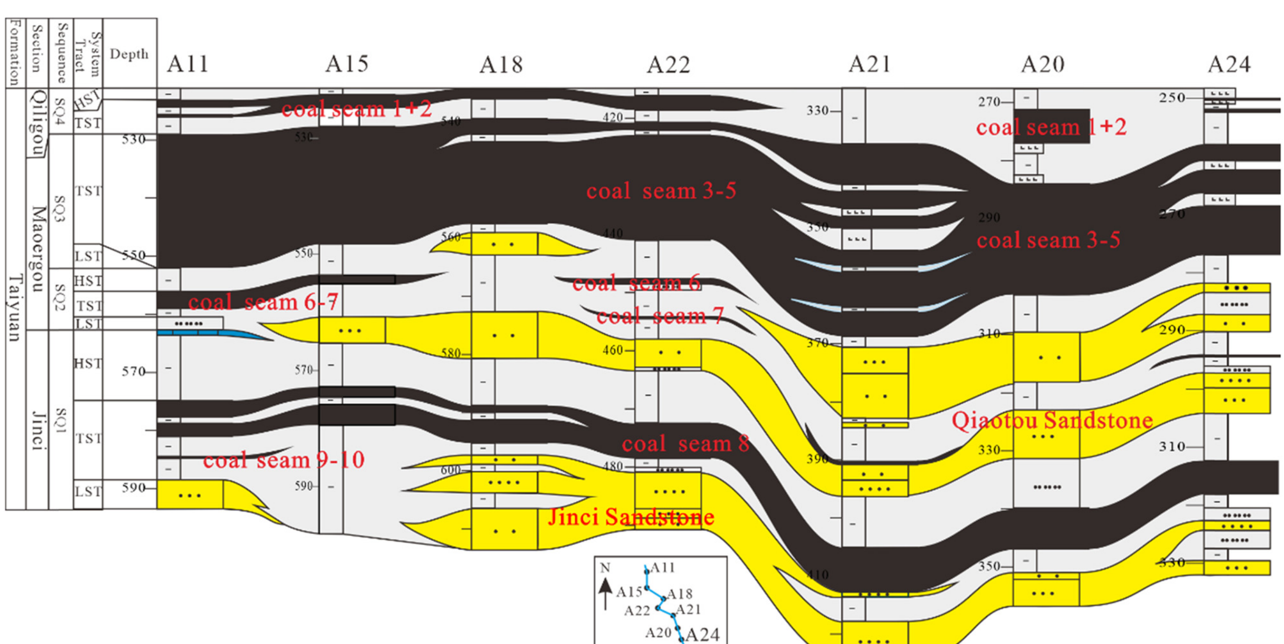

Figure 4: Sequence stratigraphic framework and connecting profiles of wells A11–A24.

regarding field outcrop profile descriptions, core sedimentary sequences, logging characteristic, curve sequence variation characteristics, paleontology, geochemistry, and other factors, and its strata are divided into four third-order sequences in detail. A sequence of the Jinci section (SQ1), two sequences of the Maoergou section (SQ2 and SQ3), and a sequence of the Qiligou section (SQ4; Figure 2).

5.2 Sequence development characteristics

The position of SQ1 is roughly the same as that of the Jinci section. The bottom boundary is the bottom of the Jinci sandstone (the transformation surface of sedimentary system), and the top boundary is the bottom of the Qiaotou sandstone (or the top of the Miaogou limestone). There are LST, TST, and HST developed in SQ1 (Figures 4 and 5). The strata thickness is in the range of 14.59–60.41 m, with an average of 31.92 m, and the largest thickness is near well A3.

In LST, Jinci sandstone is the dominant sediment. The bottom of the sandstone is usually gray–white, gray–brown fine conglomerate, or gravel-bearing coarse sandstone, which usually changes in normal grade granularity and gradually transits upward to fine-grained quartz greywacke with partially light-gray thin tuff or dark mudstone. Barrier bars and sandflat deposits of lagoonal tidal flat facies are the main sedimentary systems (mainly coarse-grained sandstone to fine-grained sandstone deposits), and some areas are underwater distributary channels filling deposits developed in the delta front (mainly fine-grained conglomerate-gravel-bearing coarse-grained sandstone to coarse-grained sandstone).

In TST, a layer of silty and fine-grained sandstone deposits in the lower part, the middle part deposits sandy mudstone and mudstone, the upper part mainly deposits at coal seam 8, and coal seams 9 and 10 developed locally, in which the top of coal seam 8 is the largest transgressive surface in the sequence.

HST mainly deposits sideritic mudstone and mudstone and locally develops argillaceous sandstone and siltstone, which are filling deposits under the background of regional regression.

The position is similar to the lower half of the Maoergou section of SQ2, with the bottom boundary is the bottom of the Qiaotou sandstone, and the top boundary is the bottom

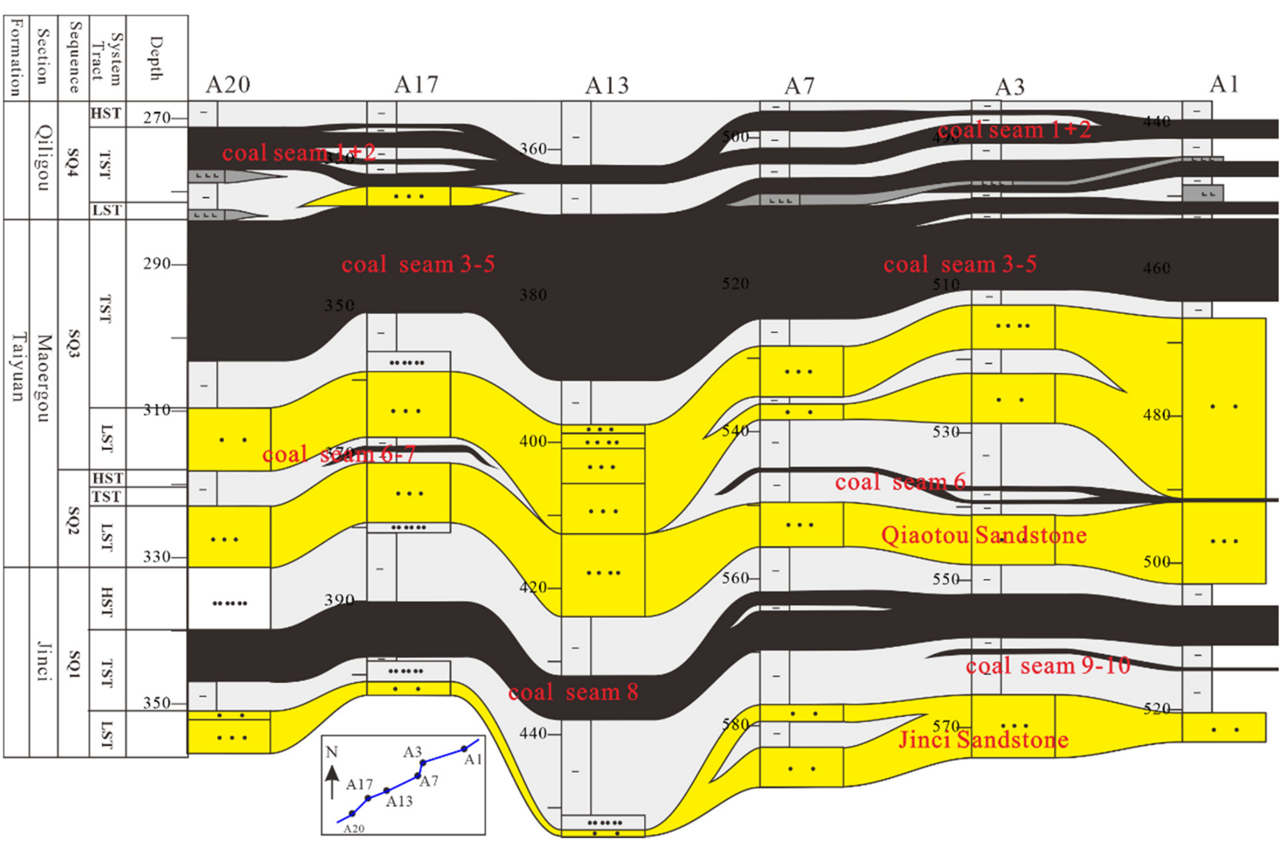

Figure 5: Sequence stratigraphic framework and connecting profiles of wells A20–A1.

of the Malan sandstone developed in the upper part of the Maoergou section (when the sandstone is undeveloped, it is the bottom of coal seams 3–5). The strata thickness ranges from 7.36 to 27.19 m, with an average of 14.2 m, and the largest thickness is near well A30. There are LST, TST, and HST developed in SQ2 (Figures 4 and 5).

The LST mainly deposits grayish-white coarse-grained sandstone to fine-grained quartz sandstone. The top surface of coal seam 6 represents the largest flooding surface in the third-order sequence. The HST is often incompletely preserved, or even missing, due to the downcutting of the upper sandstone channel during its formation, and it mainly develops dark mudstones in the interdistributary bay under the background of this regression.

The position is similar to the upper half of the Maoergou section of SQ3. The bottom boundary is the bottom of the Malan sandstone, and the top boundary is the top of coal seams 3–5. The strata thickness ranges from 24.73 to 54.52 m, with an average of 29.13 m, and the largest thickness is near well A21. LST and TST are developed in the sequence, whereas no HST is found (Figures 4 and 5).

The LST in the sequence mainly deposits light red medium-fine lithic quartz sandstone in the distributary channel. The TST deposits interdistributary bay mudstone and peat swamps during this period. Coal seams 3–5 are formed in this period, which are among the main coal seams in the study area. The top surface of coal seams 3–5 is the largest transgressive surface in the sequence and also the largest transgressive surface in the Taiyuan Formation. The HST is not developed or eroded by the upper sequence.

The position is similar to the Qiligou section of SQ4. The bottom boundary is the top surface of coal seams 3–5, and the top boundary is the bottom surface of K3 sandstone. The strata thickness ranges from 0 to 32.15 m, with an average of 17.48 m, and the largest thickness is near well A7. TST and HST developed in the sequence, and LST developed partially (Figures 4 and 5).

The LST is sporadically developed in this sequence, gravel-bearing coarse-grained sandstone and coarse-grained sandstone deposited, and mainly developed near well A17. The TST is mainly composed of argillaceous siltstone, silty mudstone, and coal seams 1 and 2. The top surface of coal seam 1 is the largest transgressive surface in this sequence. The HST mainly deposits silty mudstone, mudstone, and sideritic mudstone, which are preserved by the channel downcutting during the formation of K3 sandstone.

6 The characteristics of paleogeographic under the sequence stratigraphic framework

The sedimentary system refers to the three-dimensional lithofacies assemblage, which is genetically related to the sedimentary environment and the sedimentary process [23,24]. The purpose of clarifying its distribution characteristics is to determine the law of land–sea distribution during the sedimentary geological period of the Taiyuan Formation and the space–time distribution relationship of various sedimentary facies. Based on the research concept of “the present is the key to the past,” the lithologic assemblage characteristics and distribution rules of strata are identified, and the paleogeography of the Taiyuan Formation sedimentary period is reconstructed. Based on the analysis of the sequence stratigraphic framework and the lithofacies paleogeographic characteristics, an understanding of coal accumulation law in the sequence stratigraphic framework is proposed. In this study, the method of “single-factor analysis and multifactor comprehensive mapping” is mainly used for the distribution of sedimentary facies.

The principles for the compilation of sedimentary facies distribution maps in the study area are as follows:

1. Based on the recognition of the sequence boundary and the sequence stratigraphic framework, the third-order sequence of the Taiyuan Formation is selected as the drawing unit.
2. Fifty-five drilling cores and logging data in the study area are selected. The data points can cover the whole area to ensure the drawing accuracy.
3. Focusing on tracing the temporal and spatial succession of sedimentary facies, a single-factor parameter contour map can be created on the basis of the sequence stratigraphic framework and the results of single-well sedimentary facies analysis. Then, a comprehensive analysis and a compilation of the distribution map of sedimentary facies in each third-order sequence can be created.

Therefore, the thickness contour of sandstone, limestone, mudstone, and coal seam developed in each third-order sequence of 55 drilling cores and logging data in the study area is counted. The distribution maps of sedimentary facies in each sequence are compiled by extracting the geological information.

During SQ1, the paleotopography of the study area is generally characterized by “north low – south high,” and the whole North China Basin is generally affected by transgression events. The sea water invaded from the northwest (NW) direction, and the study area continues to receive deposits. Influenced by tectonic, paleogeography, and transgression events, a set of paleogeographic patterns with carbonate platform–tidal flat–lagoon–shallow water delta (front) deposits as the main body formed in this area. The NW corner is the direction of seawater intrusion, the carbonate tidal flat deposits are developed, and the limited subtidal flat deposits are dominant. The SW corner is a high-lying area with delta front subfacies as the main deposits, and the underwater distributary channel and interdistributary bay microfacies are developed. The underwater distributary channel microfacies is one of the main forming environments of the Jinci sandstone. Distributary bay and peat swamp microfacies are the main forming environments of coal seam 8 in this area. Tidal flat–lagoon deposits are widely distributed in the rest of the study area, in which lagoon deposits, mud flat, and peat swamp deposits are the main forming environments of coal seam 8, whereas barrier bars developed during the period are the main forming environments of the Jinci sandstone (Figure 6).

During SQ2, water withdraws from the study area. A set of shallow topography is formed with the beginning of a new round of transgression. Paleogeographic patterns are dominated by shallow water delta deposits, delta front subfacies are widely distributed, underwater distributary channels and interdistributary bay microfacies, especially underwater distributary channel microfacies. A set of sandstone strata with a large thickness, wide distribution, and good regional extensibility is deposited, which is one of the representative sandstones (Qiaotou sandstone) in this area. Interdistributary bay microfacies are locally developed in the western part, thick mudstone deposits are dominant, and thin coal seams locally developed (Figure 7).

During SQ3, the influence of regional transgression events is further expanded, and the sea level reached the maximum of the transgression, and the paleogeographic pattern is still dominated by shallow water delta deposits. Delta front subfacies (some of which are delta plain subfacies) are widely distributed, and underwater distributary channel and interdistributary bay microfacies are developed. Compared with the SQ2, the channel migrated slightly westward, and the extent of the channel decreased. The distribution of the channel remained along the direction of “NE–SW,” and the sediments are mainly thick

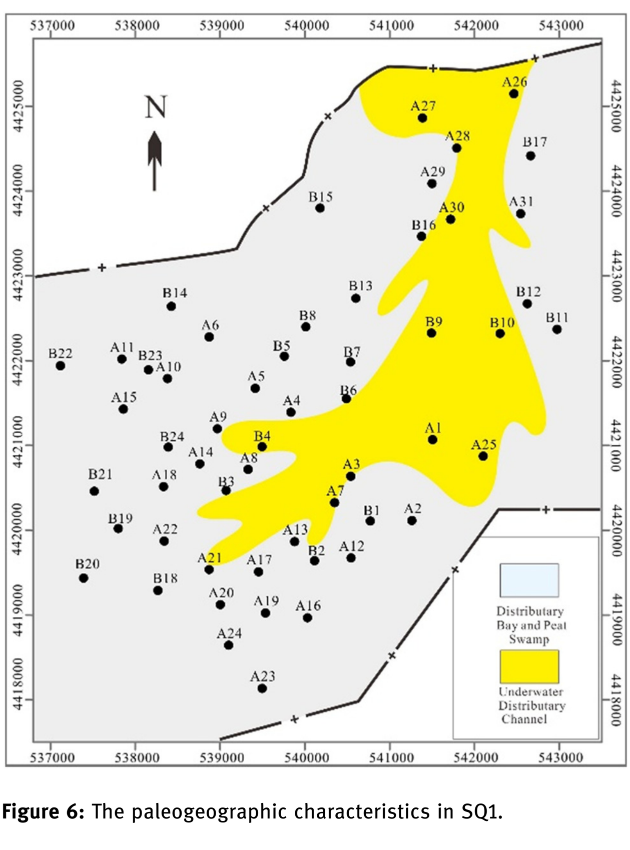

Figure 6: The paleogeographic characteristics in SQ1.

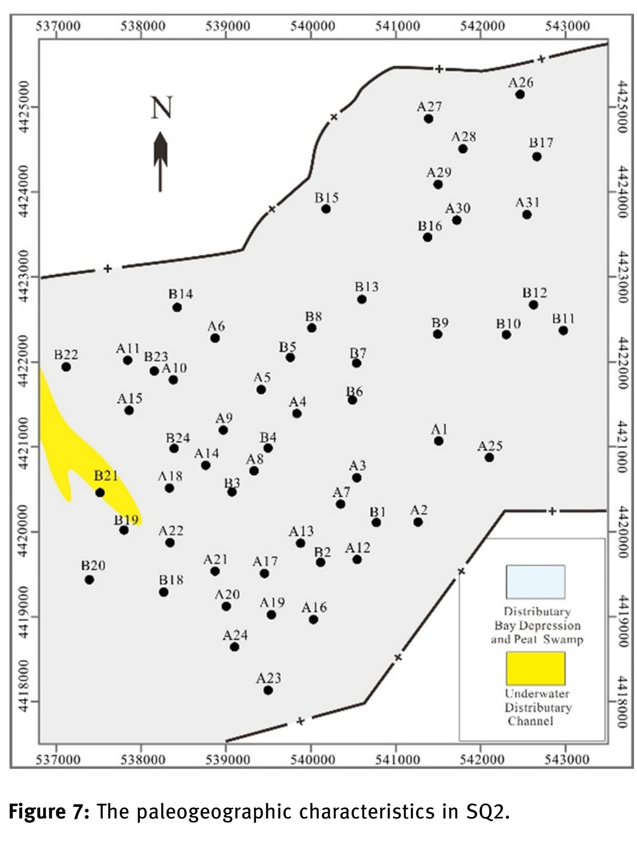

Figure 7: The paleogeographic characteristics in SQ2.

sandstone. In addition to underwater distributary channel microfacies, interdistributary bay microfacies (part of which is interdistributary depression microfacies), peat swamps, and a set of mining coal seams (dominated by coal seams 3–5) developed in this area (Figure 8).

During the SQ4, the paleogeographic pattern is still dominated by shallow delta deposits. The delta plain subfacies deposits are widely distributed, in which distributary channel, interdistributary depression, and peat swamp microfacies are developed, and the deposits are mainly composed of thick mudstone and thick coal seam. Distributary channel microfacies are locally developed in the NW corner, and the deposit is mainly composed of sandstone (Figure 9).

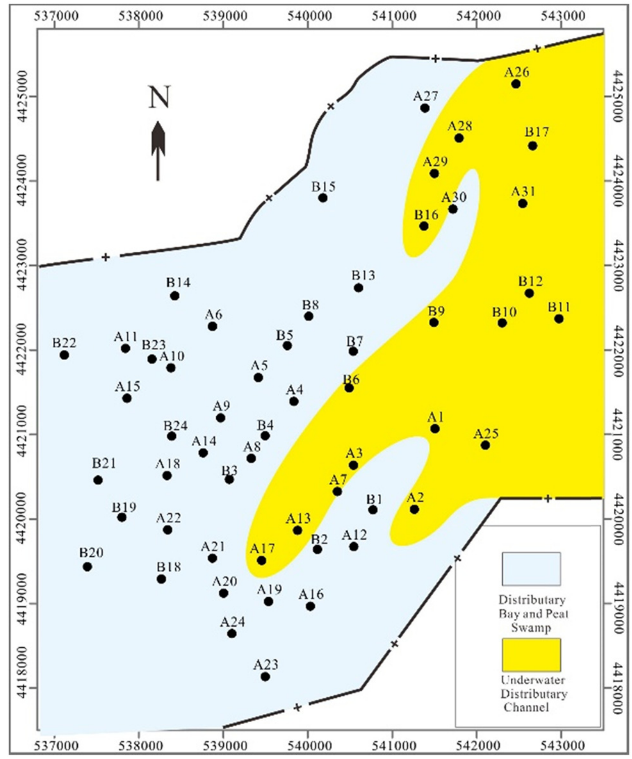

Figure 9: The paleogeographic characteristics in SQ4.

7 The distribution characteristics and coal accumulation model of main coal seams

The distribution characteristics of the main coal seams in the Taiyuan Formation are investigated based on the previous research of 55 drilling data, logging and geochemical data, the sequence stratigraphic framework, and paleogeographic restoration established in the previous chapters (Chapters 5 and 6). Thickness contour maps and the coal accumulation models of the main coal seams (3–5 and 8) are drawn.

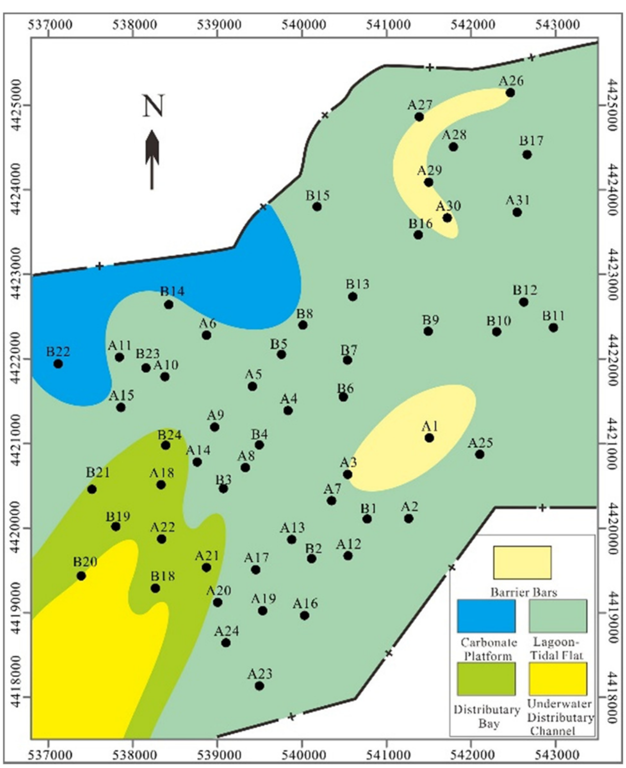

Figure 8: The paleogeographic characteristics in SQ3.

7.1 The distribution characteristics and coal accumulation model of coal seams 3–5

Coal seams 3–5 developed in SQ3 with the thickness in the range of 2.40–25.90 m (17.50 m average). It consists of 6–35 layers (generally 10–15 layers), and the average gangue content is 16%. The roof, floor, and gangue of the coal seam are mainly composed of kaolinite, sandy mudstone, and carbonaceous mudstone, locally siltstone or fine sandstone. The thickness of the coal seam in the NW is large, forming a NW-trending thick coal belt. In contrast, the coal seams in the SW and north are relatively thin (Figure 10).

According to the thickness distribution characteristics of coal seams 3–5 and the paleogeographic pattern of SQ3, the coal accumulation model of coal seams 3–5 is established (Figure 11). Due to the early “seesaw movement” in the North China Basin and the paleogeographic

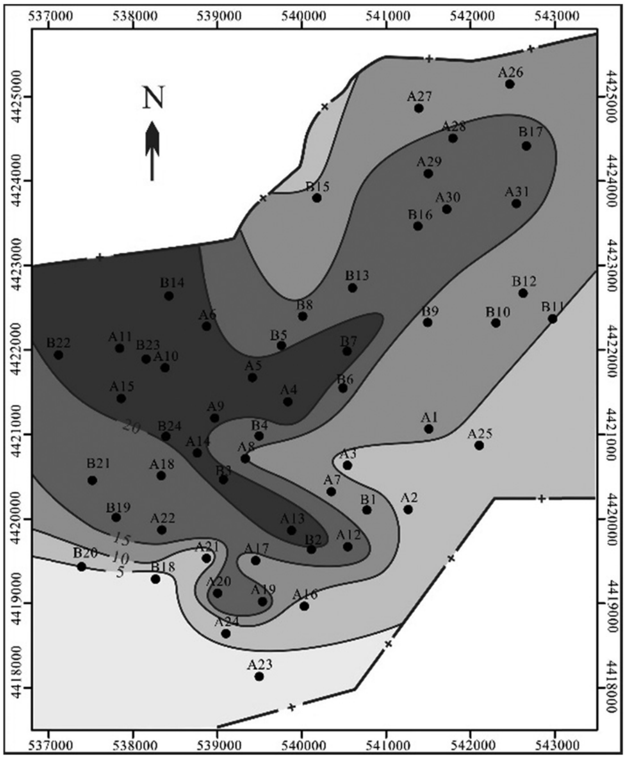

Figure 10: The thickness contour map of coal seams 3–5.

pattern changed from "south high – north low" to "north high – south low," the basement subsided and received deposits, and the shallow water delta sedimentary system is widely developed with the beginning of a new round of transgression. The development of coal seams 3–5 is obviously controlled by the sedimentary environment, which is mainly distributed in the interdistributary bay and peat swamp microfacies.

The NE part of the study area has a relatively high terrain, and the provenance comes from the NE direction. The delta plain subfacies deposits are developed in the overwater part of the delta near the provenance, whereas the underwater part of the shallow delta depositional system is dominated by delta front subfacies far from the provenance. The underwater distributary channel microfacies is dominant, and the sediments are mostly medium and fine sandstone, which is difficult to meet the development of peat swamps. In the higher part of the NE, the distributary channels (underwater) develop southward. The sediments are mostly medium-grained and fine-grained sandstones, occasionally accompanied by river diversion or "cut-off." The peat swamps developed, forming multilayered thin coal seams, or sand-peat interbeds. The channels change causes bifurcation,

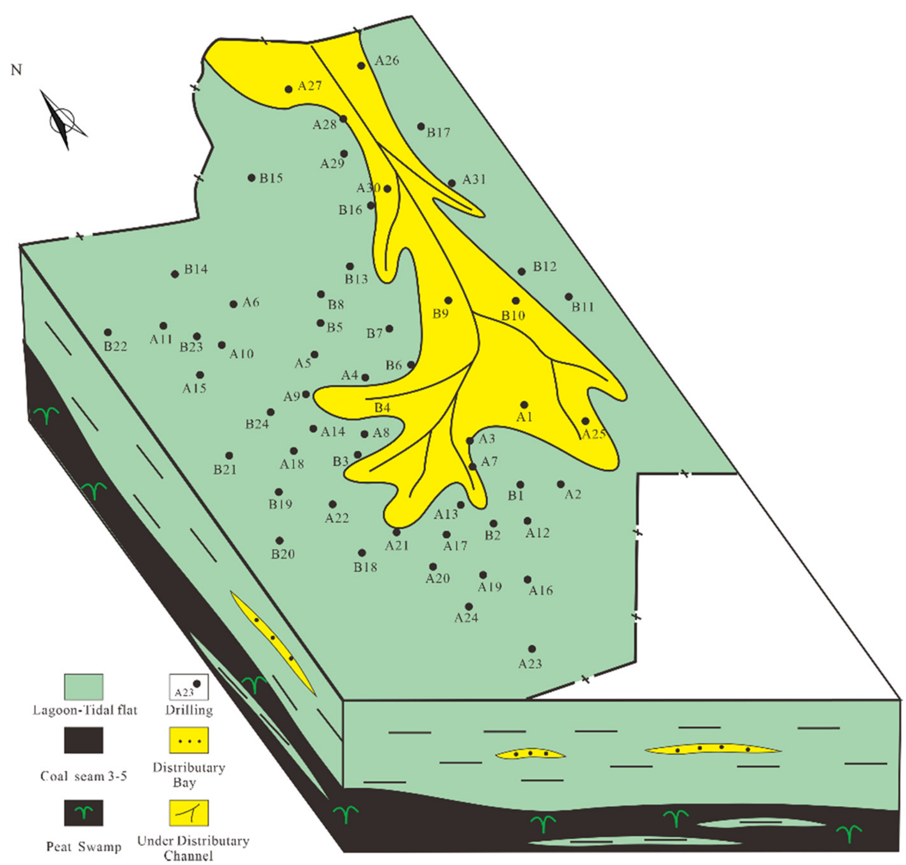

Figure 11: The coal accumulation model of coal seams 3–5.

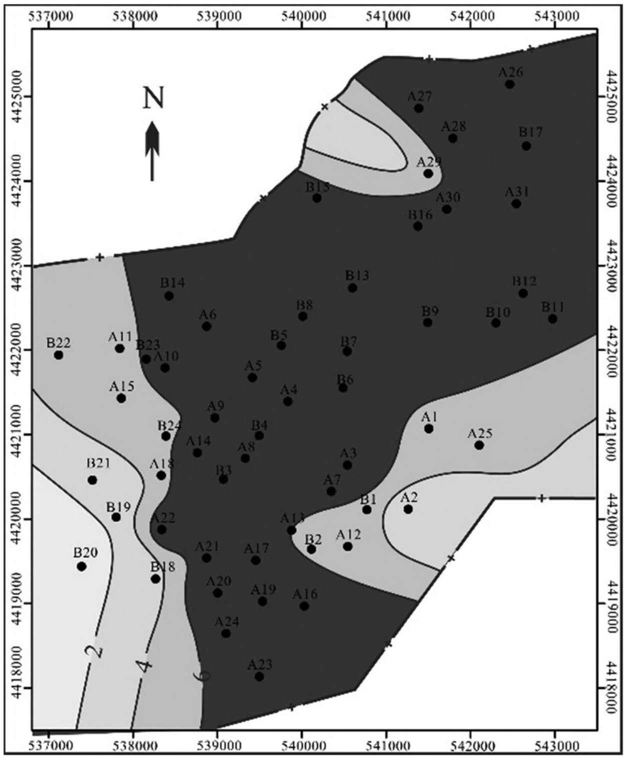

Figure 12: The thickness contour map of coal seam 8.

denudation, thinning, or even thinning out. Except for the high-lying areas in the NE, most of the study area has moderate water depth, in which distributary bay and peat swamp widely developed, forming a thick coal seams 3–5 (Figure 11).

7.2 The distribution characteristics and coal accumulation model of coal seam 8

Coal seam 8 developed in the SQ1 with the thickness in the range of 0.5–10.5 m (5.97 m average; Figure 12). Coal seam 8 is composed of 1–5 layers (generally 1–3 layers) with stable thickness in the whole area. The gangue is sandy mudstone or kaolin mudstone with a gangue content in the range of 0–23%. The direct roof is deep-gray, gray–black sideritic siltstone, sandy mudstone, and the main roof is coarse-grained quartz sandstone. The floor is mainly composed of sandy mudstone, kaolin mudstone, and siltstone.

The coal accumulation model of coal seam 8 is established according to the planar distribution characteristics of coal seam 8 and the paleogeographic pattern of SQ1 (Figure 13). The North China Basin is in a "south high – north low" paleogeographic pattern in SQ1, the whole North China platform basement began to subside and accept deposits with the beginning of a new transgression event. At this time, seawater invades the study area from NW to SW, the lagoon–tidal flat sedimentary system widely developed. Most of the northern part of the study area are located in low-lying areas. Lagoon, mud flat, and peat swamp microfacies are widely distributed, which provides necessary accommodation space for the deposit and preservation of coal seam 8. The warm and humid climate makes plants multiply in large quantities, which provides a provenance for coal seam 8. The deeper water level makes most areas of the study area in a partial reduction water environment, which provides favorable conditions for the preservation of the coal seam. The shallow water delta sedimentary system developed near the material margin in the SW corner, and the distributary bay and peat swamp microfacies are also suitable for the accumulation and preservation of coal seam 8.

In addition to the widely distributed lagoon, mud flat, and peat swamp microfacies, the underwater distributary channel microfacies of the shallow delta sedimentary system developed in the SW margin because of its relatively high terrain, relatively shallow water body, strong hydrodynamic forces, turbulent water body, and partial oxidation environment. The sediments are mostly medium-grained and fine-grained sandstones, which are difficult to meet the development of peat swamps. Rivers often have diversion changes or "cut-off work," and there is a diversion of rivers to distributary bays and peat swamps, forming multilayered thin coal seams or sand-peat interbeds. When the rivers diverted again, the original deposited coal seams are scoured, resulting in erosion and oxidation, and the coal seam experience bifurcation, denudation thinning, or even thinning out. The barrier bar microfacies developed in the southeast and NE corners with coarse sand-gravel sandstone being the main type, which is not conducive to the long-term accumulation and preservation of thick coal seams.

8 Conclusion

1. The lagoon–tidal flat and delta depositional systems developed from bottom to top in the Taiyuan Formation. The former is dominated by delta plain subfacies (including distributary bay, distributary channel, and peat swamp microfacies), and the corresponding sediment consists of sandstone, siltstone, mudstone, and coal seam. The latter is mainly composed of lagoon, peat swamp, and mixed flat and barrier bar microfacies,

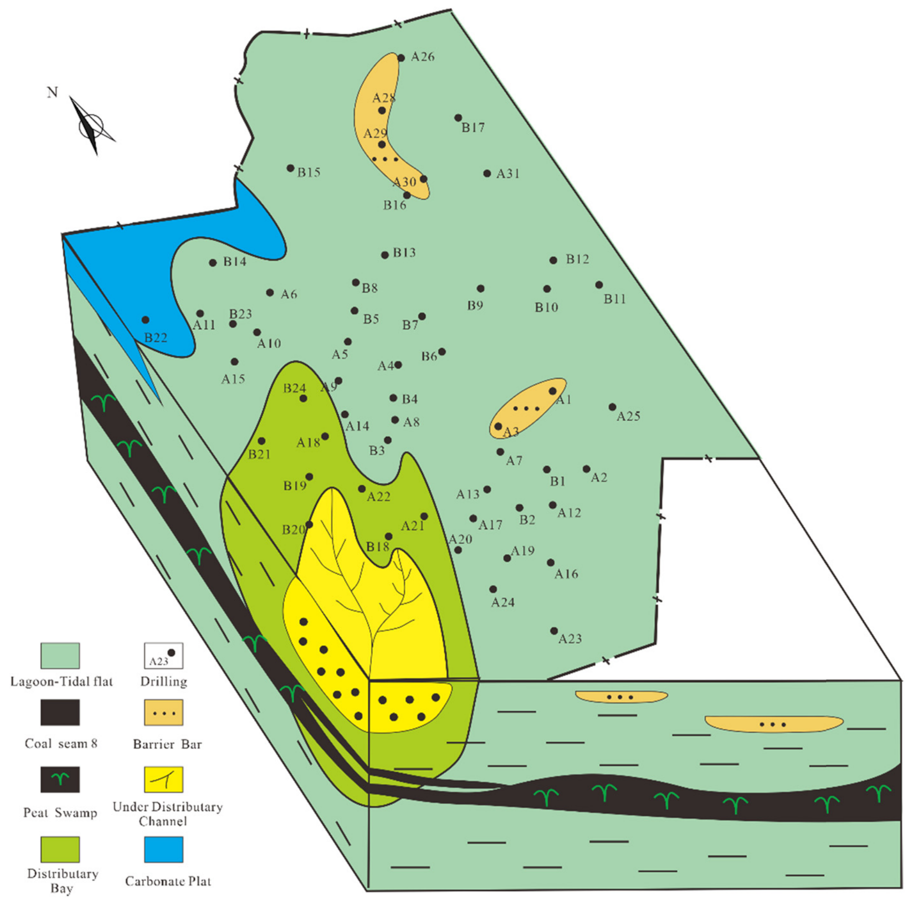

Figure 13: The coal accumulation model of coal seam 8.

and the corresponding sediment consists of sandstone, mudstone, and coal seam.

2. Through the recognition of second-order sequence boundary, system tract boundary, and third-order sequence boundary, the Taiyuan Formation was divided into four third-order sequences (SQ1–SQ4). The results exhibit that from SQ1 to SQ2, the sedimentary facies transformed from carbonate platform–tidal flat–lagoon–shallow water delta facies to shallow water delta facies, and coal seam 8 formed in interdistributary bay and peat swamp microfacies in SQ1. The sedimentary facies are dominated by shallow water delta facies in SQ3, and coal seams 3–5 also formed in interdistributary bay and peat swamp microfacies. The paleogeographic pattern was still dominated by shallow water delta in SQ4, in which interdistributary depressions and peat swamp microfacies widely developed.
3. The thickness of coal seams 3–5 is in the range of 2.40–25.90 m, with an average of 17.50 m. The widely developed distributary bay and peat swamp deposited a thick coal seam in the NE study area with a moderate water depth and sufficient fine sediment. The thickness of coal seam 8 is in the range of 0.5–10.5 m, with an average of 5.97 m. Except for several specific areas in the west and southeast corner of the study area, the thickness is generally greater than 6 m, which is controlled by the widely developed lagoon, mud flat, and peat swamp microfacies and reduction water environment.

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