Sequence Stratigraphy of the Jurassic Coal Measures in Northwestern China

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Abstract: The sequence stratigraphy of the Jurassic coal measures of northwestern China has been studied based on data from outcrop and borehole sections. Because of the geological background and the diversity of basin types, such as isochronisms of coal seams and recognition of key sequence boundaries, it is rare to summarize and correlate sequence structure and framework. The types and recognition characteristics of the sequence boundaries of the Jurassic coal measures are revealed by comparing climatic characteristics, structural styles and the base level cycle. A total of five third-order sequences and 15 systems tracts have been subdivided and the sequence stratigraphic framework has been reconstructed confirming that the thick coals accumulated in the late stage of transgression system tracts of sequence I (SQ I) and sequence III (SQ III). This idea is of important academic significance for instructing coal resources exploration, and enhancing geological effects of prospecting engineering. It is also of practical significance for guaranteeing construction of the large-scale coal production base in northwestern China, accelerating the westward development of the coal industry stratagem.

Key words: depositional system, sequence stratigraphic characteristics, Jurassic (Hettangian–Callovian), coal basins, northwestern China

1 Introduction

Sequence stratigraphy is generally regarded as stemming from seismic stratigraphy (Vail et al., 1977a, 1977b) in the 1970s. It is the study of rock relationships within a time-stratigraphic framework of genetically related strata bounded by unconformities or their correlative conformities. Based mainly on outcrop, core, well logging and other geological and geophysical data, the study of sequence stratigraphy comprehensively interprets the framework from geology combined with the related depositional environment and interpretation of paleogeography based on lithofacies. Vail et al.'s (1977a, 1977b) classic sequence stratigraphic theory was originally applied to petroleum prospecting, and later gradually applied to the analysis of coal basins by coal geologists (Li et al., 1992; Li, 1994), especially in the research on epicontinental coal-bearing basins, which has formed a complete theoretical system. Chinese scholars extensively studied and analyzed paralic coal measure sequences and have successively put forward a series of important hypotheses, such as episodic coal accumulation (Shao et al., 1992; Hao et al., 2000), coal accumulation of transgressive process (Li et al., 1999), coal accumulation of transgressive event (Li et al., 1996, 2001) and coal accumulation during the 'lag time' of marine deposits (Shao et al., 2003).

In recent years, with the discovery of thick coal seams formed in Jurassic continental basins in northwestern China, special attention has been paid to the application of sequence stratigraphy to continental coal measures. For the basins in northwestern China, because of the geological background and the diversity of basin types, the problems of the relationship between lake level change and coal formation, control factors of lake level change, development of thick coal seams in sequences are still not resolved in the case of inland lake basins, especially the isochronisms of coal seams and the identification of key boundaries in the continental alluvial system.

Based on the study of sequence stratigraphy and sedimentary facies, the paper makes a columnar section of sedimentary facies and sequence stratigraphy taking the third-order sequence as a unit. In addition, we analyze the

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regularity of the lateral distribution of the sequence stratigraphy of the key Jurassic basins in northwestern China combined with the palaeotectonic background, evolution of paleoclimate and tectonic movement characteristics.

2 Regional Geological Background

At the end of the Triassic, the collision of the Qiangtang block and the southern paleo-Asian continent caused multiple Jurassic coal-accumulating basins in northwestern China (Fig. 1), which have rich coal resources (Mao and Xu, 1999; Zhang, 1998; Ni, 2003; Chen et al., 2006; Wang et al., 2009). As a part of the Cimmerian continent adjacent to the Tethyan sea, the Qiangtang block and the South China block collided with the Asian continent, which not only caused the Qinling strait and the Songpan–Garzê trough to close, the structural deformation of the Altay, Tianshan, and Qilian Paleozoic fold belt, but also formed large-scale non-marine sedimentary basins and a series of small-scale basins in the orogenic belt, and shrunk marine sediment to the south of Karakorum, Kunlun and Bayan Har.

According to Third National Coalfield forecast (Mao and Xu, 1999), the total coal resources in the coal zones of northwestern China is 23148×108 t, of which above 99% is Lower and Middle Jurassic coal. Although there are rich coal resources, complete coal types, high-quality coal, and forecasted resource quantity has lower reliable (Chen et al., 2006; Wang et al., 2009). In addition, because of the features of the coal-formation period and multi-phase after that, tectonic superposition and transformation at different intensities, the original coal basin was strongly damaged, which greatly increased the complexity of the coal occurrence situation (Mao and Xu, 1999; Zhang, 1998; Ding, 1991; Sha, 2011; Zou, 2011). Previously, there was no systemic sequence stratigraphic study of the Jurassic coal measures in the whole zone and a lack of systematic study on the tectonic evolution of the coalfields, so that the distribution regularity and formation mechanism of the original Jurassic basins in northwestern China is not very clear (Zhang et al., 2007; Shao et al., 2009). The development of coal resources is mainly confined to an outcrop area at the basin edge and the study on the implicit coated area was non-existent, which often led in the past to coal resources exploration into a passive situation and affected the survey results. Therefore, the systemic study of sedimentary environments and sequence stratigraphy in

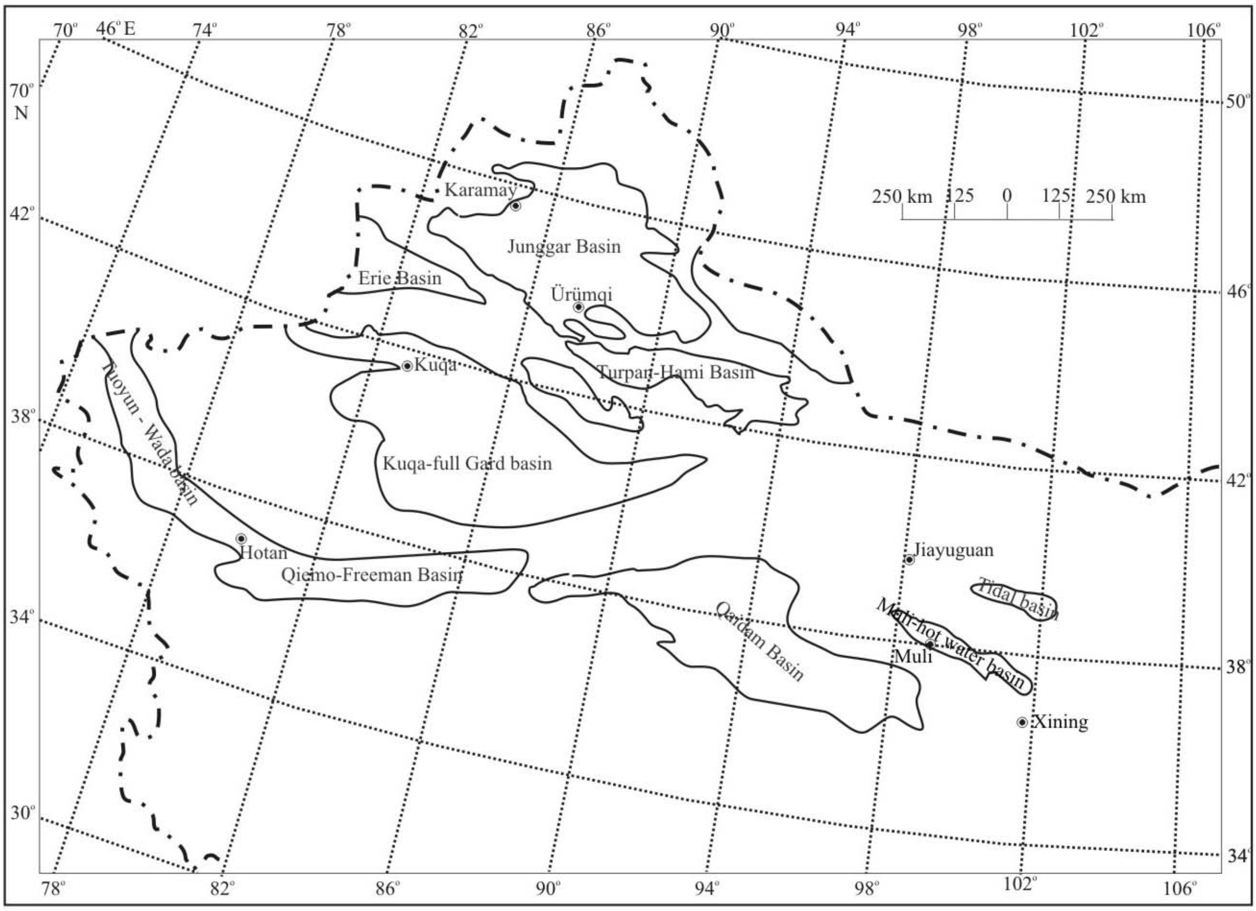

Fig. 1. Sketch map of the main coal basins in northwestern China (modified from Zhang, 1998).

the northwestern coal regions has theoretical significance for guiding future exploration and enhancing geological effects of prospection engineering.

3 Identification of Key Sequence Boundaries

The identification of key sequence boundaries is the basis for the analysis of the sequence stratigraphy (Li, 1992, 1993). Key sequence boundaries include the normal sequence boundary and the systems tract boundary (the initial transgressive surface, the maximum transgressive surface). In this paper, key boundary recognition relies mainly on the comprehensive analysis of the field outcrop section, borehole core, seismic section, and logging trace. Thus, the Jurassic sequence boundary types and identification features can be summarized into the sequence and systems tract boundaries (Table 1).

3.1 Identification of sequence boundaries

3.1.1 Unconformity surface

An unconformable surface is commonly used as a sequence boundary. Evidences to identify unconformities are: ① intermittent stratigraphic record, such as contacts between Jurassic and Proterozoic, etc.; and ② weathering surface, paleosol, basal conglomerate, etc. (Fig. 2). Unconformity surfaces usually represent a conversion surface of base level change in the long-term or extra long-term.

3.1.2 Channel erosion surface

This kind of boundary is extensively developed in boreholes and in the field section of the Jurassic coal-bearing area, e.g., the sandstones at the bottom of the Shimengou Formation in the Yuqia coalfield and the bottom of the Muli Formation in the Muli coalfield can be regarded as third-order boundaries (Fig. 3). These present as a set of irregular surfaces and filling coarse clastic rocks formed by scouring and erosion of channel, delta distributary channel or alluvial fan channel, which made significant changes in the sedimentary environment, paleontology combination, terrigenous clastic component, and trace-element composition. This is a typical sequence boundary formed under the condition of the base level rate greater than the basin sedimentary rate and minimal accommodation space.

3.1.3 Lithology, lithofacies and color transformation surface

This kind of boundary is widely developed and the interface between different lithofacies and lithlogy in the change process of the base level. It mainly presents as transformation surfaces between sandstone and mudstone, between conglomerate and coal, between conglometrate and sandstone or between mudstone, conglomerate and sandstone (Shao and Zhang, 1997, 1998). Color mutations of upper and lower strata indicate that the lithology formation conditions (paleoclimate, sedimentary

Table 1 Recognition characteristics of sequence boundaries

Number	Sequence boundary types	Geological features
1	unconformity surface	regional unconformity surface, weathering surface, paleosol
2	channel scouring erosion surface	unconformity scouring valley, coarse grain from the edge of the basin and the basin, thick channel filling deposit
3	Lithology, lithofacies and colour transformation surface	lithology, lithofacies mutation, depositional facies mutation, colour mutation
4	the initial transgressive surface	GR increasing rapidly while apparent resistivity decreasing rapidly for the first time
5	the maximum transgressive surface	black oil shale, mudstone, coal bed, logging trace turn

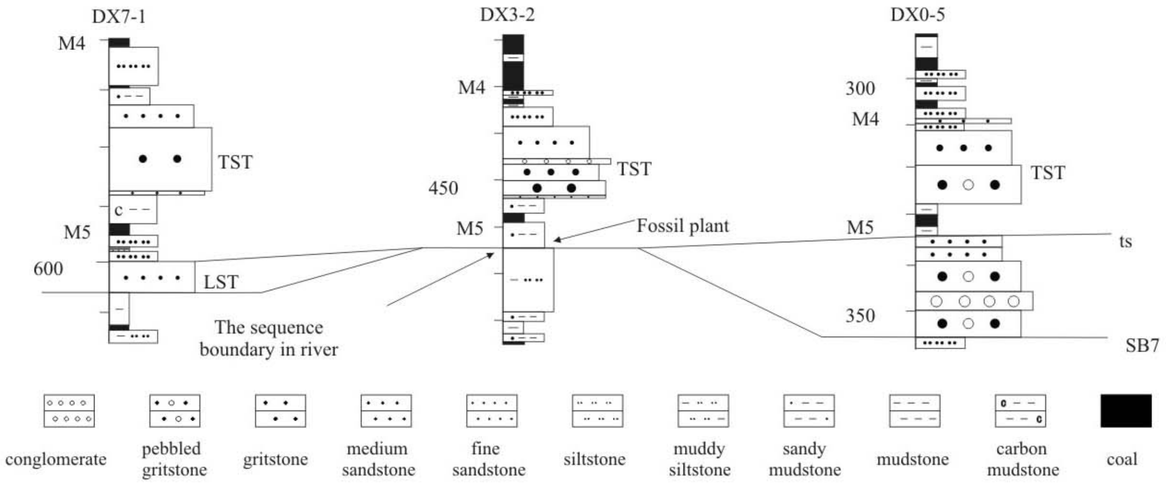

Fig. 2. Features of the interchannel sequence boundary of the Yuqia coalfield in northern Qaidam basin. (unit: m)

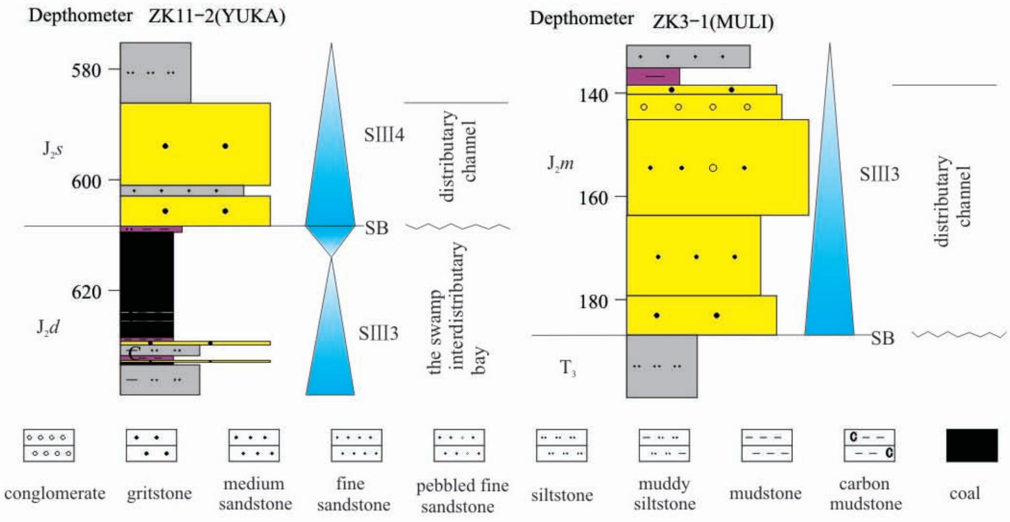

Fig. 3. Sequence boundary features of the channel erosion surface in the Yuqia coalfield of northern Qaidam basin and the Muli coalfield in Muli-Reshui basin. (unit: m)

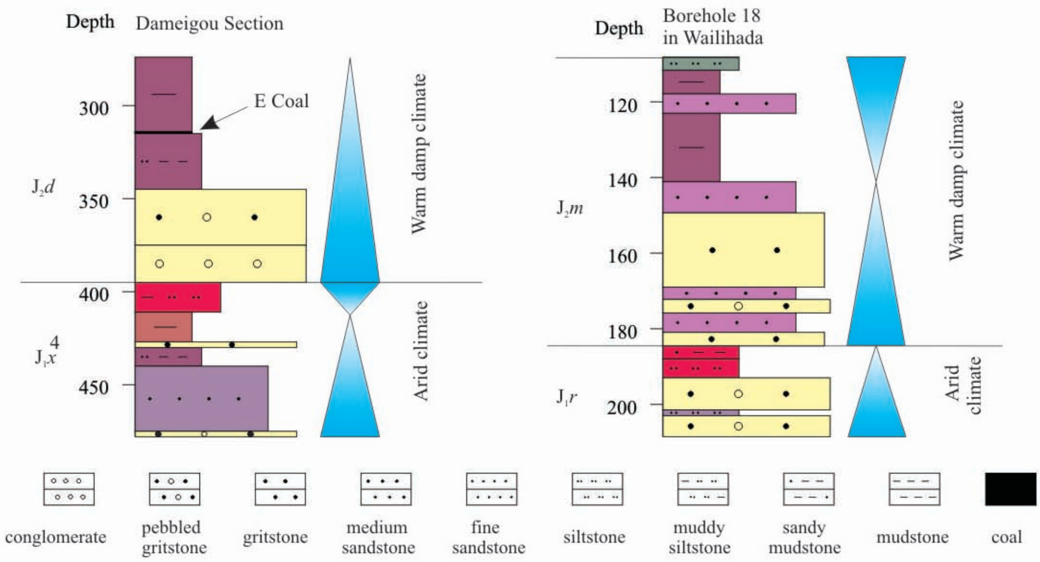

Fig. 4. Sequence boundary features of the color and lithological transformation in the Wailihada mining area of Muli-Reshui basin and the Dameigou section of northern Qaidam basin. (unit: m)

environment, etc.) are clearly different (Liu and Zeng, 1985). Surfaces showing abrupt changes of color are regarded as sequence boundaries, e.g., the boundary between the purple mudstone of the top Xiaomeigou Formation and the overlying gray sandy conglomerate at the bottom of the Dameigou Formation in northern Qaidam basin; the boundary between the purple mudstone of the top Reshui Formation and the overlying gray sandstone at the bottom of the Muli Formation in the Muli–Reshui basin (Fig. 4).

3.2 Recognition of the initial transgressive surface

The initial transgressive surface is the surface formed when lake water crossed a slope break or a low incised valley for the first time. In the study area, the bottom boundary of fine-grained rock such as mudstone, silty mudstone, siltstone over a channel sandy conglomerate is regarded as the initial transgressive surface, which is coincident with the sequence boundary in the area without a channel developed, e.g., the siltstone and mudstone at the bottom deltaic interdistributary swamp over conglomerate and sandstone of the Xishanyao Formation is the initial transgressive surface in the Junggar basin.

3.3 Recognition of the maximum transgressive surface

This surface is a sedimentary surface formed at the maximum rates of accommodation space increasing and base level rise, and the maximum water depth in a base level cycle. Its identification characteristics are: a set of sedimentary sequences that become thinner and darker upward; the darkest lithofacies are lakeshore, shallow lake, semi-deep lake facies mudstone, silty mudstone and oil shale. When this lithology presents as relatively greater thickness, its bottom is the maximum transgressive surface. When the darkest lithofacies repeats on the section, the bottom of the thickest horizon upward is the maximum transgressive surface, e.g., the mudstone bottom of the semi-deep lake over the SQ IV delta plain conglomerate, the siltstone of the Qingtujing Formation in the Chaoshui basin is the maximum transgressive surface.

The above identification principles of the boundaries are integrated and applied in the study of the Jurassic sequence stratigraphy in northwestern China. Among them, lithology, lithofacies cycle characteristics are the main references; logging traces and seismic profiles, etc., are auxiliary references, which can verify lithology, lithofacies characteristics to increase the accuracy and reliability of the sequence stratigraphy study.

4 Establishment of Regional Sequence Stratigraphic Framework

In the study of Jurassic sequence stratigraphy in northwestern China, Vail's opinion is applied in the definition of sequence and the division of systems tract (Vail et al., 1977, 1988). According to the recognition principle of sequence boundary, the Early and Middle Jurassic coal measures of northwestern China have been divided into five third-order sequences (Table 2), of which there are two sequences in the Early Jurassic (SQ I and SQ II) and three in the Middle Jurassic (SQ III, SQ IV and SQ V). The sequence level is roughly equivalent to Vail's third-order sequence (Vail et al., 1977, 1988). SQ I corresponds to the Hettangian, Sinemurian and Pliensbachian of the Lower Jurassic; SQ II corresponds to the Toarcian of the later Early Jurassic; SQ III corresponds to the Middle Jurassic Aalenian and Bajocian; SQ IV corresponds to the Bathonian in the Middle Jurassic; and SQ V corresponds to the Middle Jurassic Callovian.

4.1 Division and characteristics of sequence stratigraphy

The characteristics of sequence stratigraphy and systems tract are analyzed taking the northern Qaidam basin as an example below.

Sequence I: this sequence corresponds with the first, second, third members of the Lower Jurassic Xiaomeigou Formation (Fig. 5). The bottom boundary is a regional unconformity surface formed in the Indosinian movement. Braided delta facies–lacustrine facies are developed. The lowstand systems tract (LST) is composed of braided channel sediment, which reflects the LST deposition of the initial faulted stage, while the transgressive systems tract (TST) consists of an interdistributary bay of the top member 1 and bottom member 2, and semi-deep and deep lacustrine facies sediments of the top member 2, and the highstand systems tract (HST) is dominated by deep lake, bay, and braided delta sedimentation.

Sequence II: this corresponds with the fourth member of the Xiaomeigou Formation. The bottom surface is an erosion surface at the bottom of a distributary channel of a meandering river delta, mainly TST. The transgressive systems tract is composed of a subaqueous distributary channel and levee of a meandering river delta; the HST is dominated by purple mudstone of a flood basin and crevasse splay sedimentation.

Sequence III: this sequence corresponds to the Middle Jurassic Dameigou Formation. The bottom surface in Dameigou region is an erosion surface at the bottom of a braided channel, with a regional unconformity in other regions. The LST is composed of braided channel sedimentation, presenting in lithology as an ashen channel conglomerate, pebbled sandstone, sandstone and fine sandstone. The TST consists of an interdistributary bay and crevasse splay of a meandering river delta, where the main mineable coal seams developed (coal 6, coal 7, and group F) with simple structure and good continuity in northern Qaidam basin, thus reflecting that this transgression reached its highest, the lake depth changed slowly at that time, which caused an accommodation space duration, thus favoring rapid and sustained

Table 2 Sequence stratigraphic subdivision of the Early and Middle Jurassic coal measures in large and medium-sized coal basins

Series	Stage	Junggar Basin	Ili Basin	Turpan-Hami Basin	Kuqa-Manjiaer Basin	Tuoyun- Hotan Basin	Qaidam Basin	Third-order sequence
Middle Jurassic	Callovian	Toutunhe Fm.	Aiwergou Fm.	Qiketai Fm.	Qiakemake Fm.	Taerga Fm.	Shimengou Fm.	SQ5
	Bathonian			Sanjianfang Fm.				SQ4
	Bajocian	Xishanyao Fm.	Hujiertai Fm.	Xishanyao Fm.	Kezilenuer Fm.	Yangye Fm.	Dameigou Fm.	SQ3
	Aalenian							
Lower Jurassic	Toarcian	Sangonghe Fm.	Jirentai Fm.	Sangonghe Fm.	Tangxia Fm.	Kangsue Fm.	Xiaomeigou Fm.	SQ2
	Pliensbachian	Badaowan Fm.	Suaersuhe Fm.	Badaowan Fm.	Ahe Fm.			SQ1
	Sinemurian					Shalitashen Fm.		
	Joseph Tang				Talikeqi Fm.			

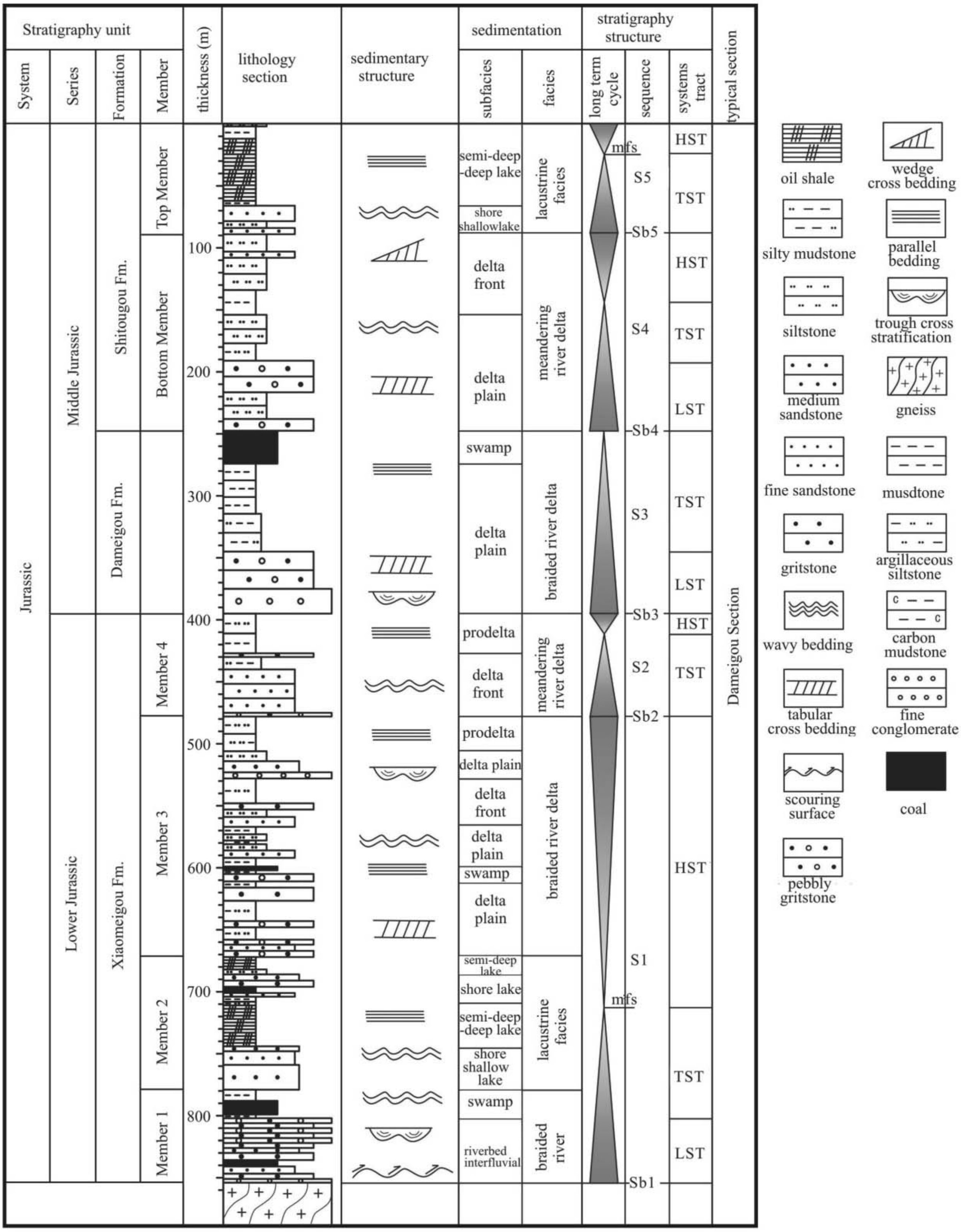

Fig. 5. Comprehensive depositional facies and sequence stratigraphic column of the Lower and Middle Jurassic in northern Qaidam basin (modified from Lu et al., 2006).

accumulation of peat.

Sequence IV: this sequence is the lower member of the Shimengou Formation and developed in the whole area. The bottom surface is an erosion surface at the bottom of the distributary channel of a meandering river delta plain. The LST consists of many distributary channels with mainly lithologies of pebbled sandstone and medium coarse-grained sandstone. The TST is composed of an

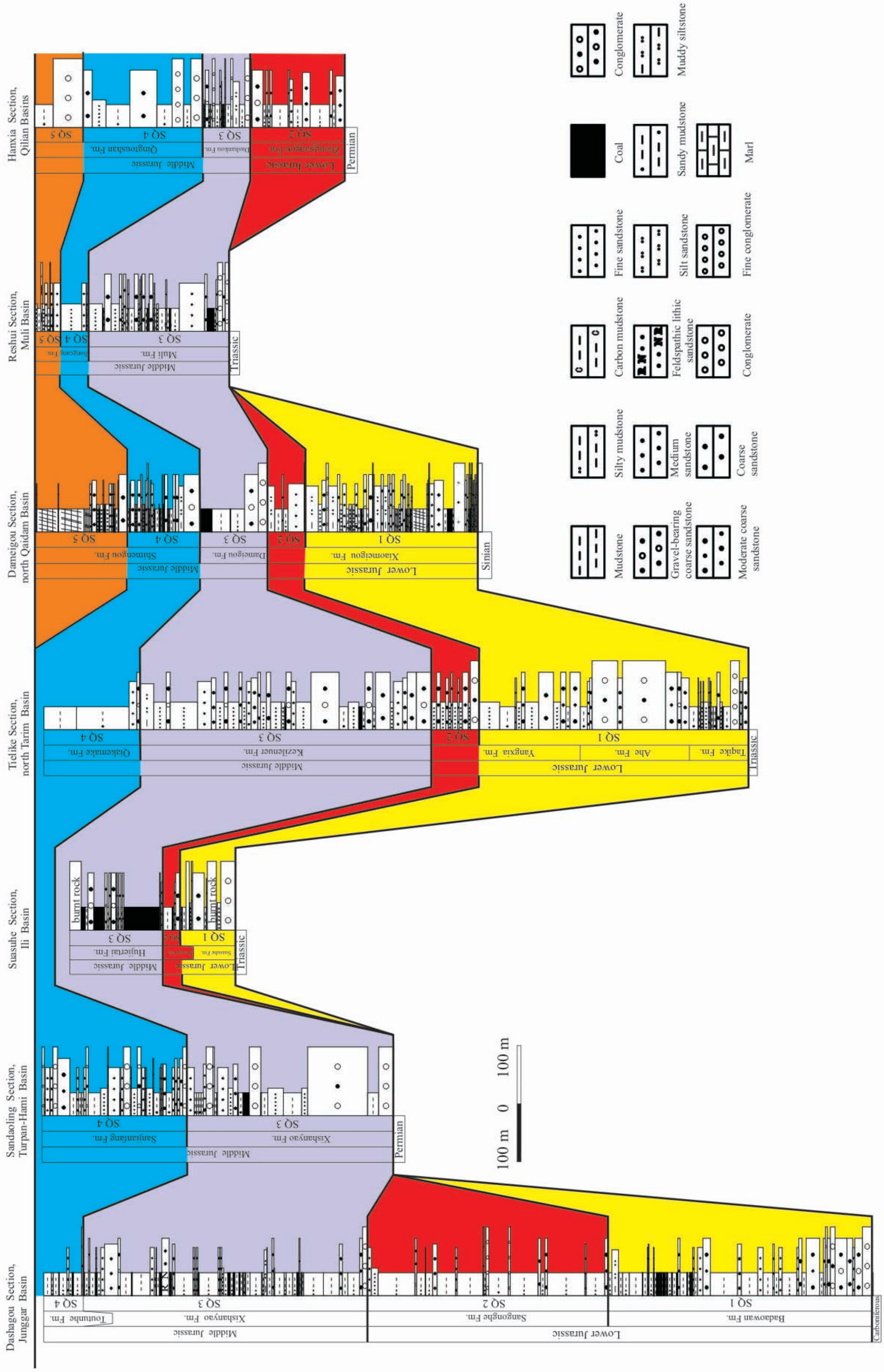

Fig. 6. Correlation of the sequence stratigraphy framework of the Early and Middle Jurassic of the main coal basins in northwestern China.

interdistributary bay of the lower delta plain. The HST consists of local delta front sedimentation. In the sequence period, a fast rising rate of lake water, a big change in accommodation space, rapid accumulation, and a thinner sedimentary thickness are not conducive to continuing peat development and accumulation.

Sequence V: this sequence is the top member of the Shimengou Formation and developed basically in the whole area. The bottom surface is an erosion surface at the bottom of a distributary channel of a delta plain.

4.2 Lateral distribution of sequence stratigraphic units

In the northwestern China areas, different basin types, deposit characteristics and denudation degrees within the late stage led to different developments of SQ I– SQ V in each basin, missing sequences in some basins. The sequence stratigraphy framework of the Jurassic coal measures in the different basins is divided and correlated according to the main coal-bearing sections of each basin (Fig. 6).

Sequence I: this sequence is located in the early and middle Early Jurassic and distributed almost in all large and medium-scale basins but developed in small scope. The sequence boundary is a regional unconformity surface (channel scouring surface). During the early stage of transgression, the braided delta sedimentary system was developed and the peat swamp developed in its interdistributary bay with the base level rising, accommodation space increasing and plants growing luxuriantly, which formed the group B and C coal seams. In the late stage of transgression, oil shale sedimentation predominates with the base level rising rate increasing, and the water suddenly deepening. In the highstand, the braided delta sedimentation developed again with the base level declining and lake retreat, and thin coal seams formed when peat accumulated but with short duration in the interdistributary bay.

Sequence II: this sequence is locally distributed in the Juggar, the Ili, the Qaidam and basins of Qilian mountain area. The sequence boundary is a channel erosion surface (fluvial or lacustrine delta distributary channel). No coal developed in this sequence under the hot and arid paleoclimate.

Sequence III: this sequence corresponds with the Aalenian and Bajocian and is distributed widely in the northwestern coal basins. The sequence boundary is mostly an erosion surface at the bottom of a lacustrine delta distributary channel. In the early stage of transgression, the lithology changed gradually from pebbled sandstone, sandstone to fine-sandstone and siltstone upward with the base level rising, and the accommodation space increasing gradually. It presents as a retrogradational type with the sedimentary facies changing into braided delta from braided river. In the late stage of transgression, the base level rise was slow or stopped, and the low accommodation space stable. Plants grew luxuriantly, swamps developed extensively and peat continued to accumulate in the smooth terrain especially in the interdistributary bay, so that thick coal seams (coals F or 7) are distributed extensively. That some coal seams deposited directly on bedrock shows that peat swamp could develop on smooth bedrock with a stable base level and low accommodation space. This sequence is the important coal-bearing sequence in the area, with thick coal seams formed in the late stage of transgressive (end of rising semi-cycle).

As we have shown, this sequence is a very important coal-bearing sequence in northwestern China. In the Junggar, the Turpan-Hami, the Ili, the Qaidam, the Qilian corridor basins and other basins, coal seams are well-developed, with good continuity and great thicknesses from several to several hundred meters.

Sequence IV: this sequence is developed widely in coal-bearing basins. The sequence boundary is mostly a scoured surface of the bottom of a fluvial delta plain, which consists of the base level rising and falling semi-cycles. Overall, lowstand and highstand systems tracts are comparatively well developed, and the transgressive systems tract deposit time is short, with a limited stratigraphic thickness. The highstand systems tract clearly presents as a progradational stacking pattern, e.g, the Sanfangjian Formation of the Turpan-Hami basin, the lower Shimengou Formation of northern Qaidam basin, etc. Compared with SQ III, the coal seam thicknesses are thinner because of the big change in the velocity of water rise and fall, which did not provide enough time for peat accumulation.

Sequence V: this sequence corresponds to the Callovian. The sequence boundary is mostly an erosion surface of the bottom of a fluvial delta plain. The late denudation of the sequence has few residues in several basins in Xinjiang, but the residual thickness in the northern margin of Qaidam basin. The sequence consists of two asymmetric semi-cycles, the transgressive systems tract comparatively developed, the stratigraphy presents as a retrogressive and agradational stacking pattern, consisting mostly of siltstone, mudstone and oil shale, with coal seams undeveloped, or only thin seams or as a coal line deposit seen in the local area of the basin.

According to above analysis, mineable thick coal seams are mostly developed in SQ III and SQ IV because of continuous peat accumulation in the late transgressive stage.

5 Discussion

It is hard to divide sequences because of unbalanced stratigraphic distribution caused by the basin stratigraphic diversity and the tectonic movement within the continental basins in northwestern China. In addition, sequence division has obvious differences owing to the discrepancy in concrete location and the geological data of the basins. Therefore, there is no unified sequence framework based on sequence division in northwestern China. The Badaowan Formation–Xishanyao Formation in the Juggar basin was divided into four third-order sequences based on logging and seismic data by Bao et al. (2002). The Early and Middle Jurassic of the Turpan-Hami basin was divided into seven third-order sequences according to characteristic sedimentary cycles and seismic sections by Shen et al. (2001). The Badaowan Formation–Xishanyao Formation of the Yanqi basin was divided into two third-order sequences on the basis of tectonic movement and climatic conditions by Qiu et al. (2001). Wu et al. (2005) divided the Jurassic of northern Qaidam basin into seven third-order sequences through study of well sections and limited seismic sections. These analyses were too limited and there was no correlation in the whole area. Poor understanding of the Jurassic coal measures often led to coal resource exploration in passive situations and affected survey results.

The present study summarizes the sequence stratigraphy in northwestern China applying the theory of classic sequence stratigraphy based on field data and study reports. Ours is the first attempt to establish a regional sequence stratigraphy framework of the continental basin group in the region and, therefore, is of important academic significance for instructing coal resource exploration, and enhancing the geological effects of prospecting engineering. Practical outcomes aid the guaranteed construction of large-sized coal production bases, and the acceleration of the westward development of the coal industry stratagem.

6 Conclusions

In the Jurassic coal measures of northwestern China, six sequence boundaries have been identified based on regional unconformity surfaces, channel scouring surfaces, lithology, lithofacies and color transformation surfaces. Five third-order sequences have been subdivided, which correspond to the Hettangian–Pliensbachian, Toarcian, Aalenian–Bajocian, Bathonian and Callovian, respectively. In the late stage of the transgressive systems tract of sequence I and sequence III, thick coal seams were extensively developed when plants grew luxuriantly, swamps developed widely and peat continuously accumulated in the interdistributary bay. It is considered that the accommodation space increasing rate held the balance with the rate of peat accumulation for a long time, which met easily the coal-accumulating conditions of thick coal seams with the lake level (base-level) constantly uplifted.

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