Sedimentary system and coal seam distribution in the coal-bearing sequence stratigraphic framework in the Paleogene Meihe Formation (Meihe Basin, NE China)

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Abstract

The Meihe Basin is one of the important Paleogene coal-bearing fault basins of northeastern China in the Dunhua-Mishan Fault Zone. The Lower Coal-bearing Member and the Upper Coal-bearing Member are the primary layers studied. Through field observation, core description and observation under microscope, fan delta facies and lake facies are observed as the main sedimentary facies of the coal-bearing layers, and subfacies of fan delta plain, fan delta front, shallow lake and swamp have also been recognized. Coal seams primarily accumulated in the subfacies of swamp and fan delta plain. The study on sequence stratigraphy is based on outcrop section, well-log analysis, core observation and geochemical analysis. From the Lower Coal-bearing Member to the Upper Coal-bearing Member, three third-order sequences have been recognized; the Lower Coal-bearing Member developed in Sequence I and the Upper Coal-bearing Member developed in Sequence III, both sequences have developed the lowstand systems tract (LST), the transgressive systems tract (TST) and the highstand systems tract (HST).

Single-factor analysis and the multifactor comprehensive mapping method have been used to rebuild the lithofacies palaeogeography of each system tract in Sequence I and Sequence III. Through analysis of contour maps of total stratum thickness, sandstone thickness and sand content, as well as contour maps of thicknesses and numbers of layers of coal seams, the results indicate that the sedimentary environments and coal seam distributions are variable in different system tracts. Coal types accumulating in the swamp facies are primarily developed in the transgressive systems tract (TST) and the highstand systems tract (HST) of Sequence I with a wide range of continuous and large thicknesses and may be mined commercially. Both the balanced accommodation growth rate with peat accumulation rate and little or no influence from sediment supply and channel migration promote to form the stable coal accumulating environments.

Introduction

The occurrence and distribution of coal is influenced by base level changes, which futher influenced by ‘accommodation’, sediment supply, peat-accumulation rate and climate changes (Powell, 1875; Buillit et al., 2002; Cross, 1988; Diessel, 1992; Diessel et al., 2000; Bohacs and Suter, 1997; Van Wagoner et al., 1990; Wilbus et al., 1988; Flint and Hampson, 1995; Fasset, 1986; Opluštil et al., 2013). Studies relating to coal-bearing layers forming in sequential stratigraphic frameworks have been published in the literature. Ryer (1981, 2009) has noted that the thickest and most widely distributed coal seams in delta sand bodies accumulated mainly near the maximum flooding surface. Bohacs and Suter (1997) have found that thick and widely-distributed coal seams are accumulated in the TST, as continuously increased accommodation is prevalent. Diessel (1992, 2007) investigated different coal seams developed in eight countries and found that the commercial seams were mainly developed in the middle stages of the TST and HST. Shao et al. (2003a, 2003b) also proposed that the accumulation of commercial seams was related to the maximum flooding surface of the TST. The research mentioned above was conducted only in marine basins, while most of the coal-bearing basins in China are non-marine basins with coal seams developed mainly in the river-delta-lake sedimentary system. Non-marine basins are mostly small-scale and have close and multiple provenances, as well as, for instance, abrupt slopes, and are easily influenced by paleoclimate and paleostructure; as a result, coal seams in non-marine basins have variable thicknesses and distributions in different system tracts (Liu et al., 2002; Shanley and MeCabe, 1994).

The Meihe Basin is an important coal-bearing fault basin in northeastern China, and the coal is mainly developed in fan delta and swamp environments. The most important commercial coal seam is the 12th coal seam of the Lower Coal-Bearing Member (Hu et al., 1996a, 1996b; Hu, 1990; Wu et al., 2008; Wang et al., 2008). Wu et al. (2008) and Hu et al. (1996b) noted that paleoenvironment is one of the factors directly affecting the occurrence and distribution of Meihe Basin coal and that coal was mainly deposited in the peat mire between the fan delta body and the swamp of fan delta plains, as well as in the swamps of lakes accumulating silt. Bai et al. (2014a, 2014b) noted that fan delta plain and swamp are the main coal accumulating environments in the Meihe Basin and the organic matter type of coal is type II_2 with an organic matter source of terrigenous higher plants. The coal was mainly deposited in a reducing environment of freshwater. Most of the studies are concerned with the whole environment and factors affecting coal accumulation in the Meihe Basin, while the sequence stratigraphy of coal-bearing layers has not been conducted. Based on the understanding of sequence stratigraphy, well-log analysis, geochemistry and sedimentology presented in this paper, the coal distribution and paleoenvironment evolution in the sequence stratigraphic framework of the Paleogene Meihe Formation are studied in detail to establish the development model of coal accumulation in small-scale fault basins.

Geological Setting

The Meihe Basin is a Paleogene fault basin in the Dunhua-Mishan Fault zone with coexisting energy minerals of coal and oil shale being present. This basin has a graben geometry and is bound to the NW and SE by two major strike-slip faults, which directly controlled the thickness and distribution of the coal-bearing layers of the Meihe Formation (Wu et al., 2008; Hu et al., 1996a, 1996b; Wang et al., 2008) (Fig. 1).

The basin fill (Meihe Formation) is up to 1000 m thick and overlies various basement units, including Cretaceous sedimentary rocks and Presinian strata. The Meihe Formation consists of five members (Fig. 1); from bottom to top, they are the Conglomerate Member, the Lower Coal-bearing Member, the Oil Shale-bearing Member (Mudstone Member), the Upper Coal-bearing Member, and the Green Rock Member (Wu et al., 2008; Hu et al., 1996a, 1996b; Wang et al., 2008). The Lower and Upper Coal-bearing Members were deposited in a warm and humid climate, and the Oil shale-bearing Member was developed in the alternating wet and dry climate (Hu, 2013).

The Conglomerate Member mainly consists of alluvial fan and fan delta environments with sediments of conglomerate, sandy conglomerate and coarse sandstone interbedded with red mudstone. The Lower Coal-bearing Member and the Upper Coal-bearing Member mainly consist of lake and fan delta sediments, with the commercially important 12th coal seam developed in the Lower Coal-bearing Member.

Rocks formed in shallow lake and semi-deep to deep lake environments comprise the majority of the Mudstone Member. As there is Quaternary cover up to 10 m in thickness, few cores have been drilled into the Green Rock Member (Wu et al., 2008; Hu, 1990; Hu et al., 1996a; Bai et al., 2014a, 2014b). The Lower Coal-bearing Member and the Upper Coal-bearing Member are the layers studied in this article.

Sampling And Methods

Unweathered samples of gray and brown siltstone, mudstone, oil shale and coal were collected from borehole MH2011-10. Eight samples are from the Lower Coal-bearing Member from depths of 657.9 m-754.4 m and thirty-two are from the Upper Coal-bearing Member from depths of 52.8 m-546.6 m (Fig. 2).

The trace element concentrations were determined using Chinese standard GB/T 14506.30-2010 using a Thermo Scientific ELEMENT high-resolution ICP-MS at the National Geological Experiment Center of China. Total organic carbon (TOC) was tested using a LECO CS-230 instrument following standard GB/T 19145-2003, by the Mineral Resources Supervision and Inspection Center of the Ministry of Land (Changchun, China).

Single-factor analysis and the multifactor comprehensive mapping method proposed by Feng (2004) have been used to rebuild the lithofacies palaeogeography of each system tract. Single factors indicates these that can independently and quantitatively reflect the sedimentary environments of the studied area such as the water depth, energy strength, stratum thickness, rock types, structure, mineral composition and rock color etc. Performing a statistical analysis on the content of each single factor and making the corresponding contour maps first, then making comprehensive judgment, the quantitatively lithofacies palaeogeography can be rebuilt.

Sedimentary Environment

Amount of work about the characteristics of sedimentary environment in Meihe Basin has been made by our research team, and some papers about this are under review or in published in some academic magazines (such as Bai et al., 2014 a; Bai et al., 2014b; Wang, 2012; Yao, 2012; Hu, 2013). Outcrop in the field and core observation, well-log analysis, microscopic observation, grading analysis combined with the whole sedimentary setting of Dunhua-Mishan Fault Zone have been carried out, and the main sedimentary environments of the two coal-bearing members are identified according to the rock association, lithological changes, sedimentary structure, characteristic parameter of particles, particle size distribution and features of well logs. Fan delta and lake are the main sedimentary facies. Subfacies of fan delta plain and fan delta front, microfacies of distributary channel with a scour-and-fill structure, distributary interchannel with thin coal seams and carbonaceous mudstone, as well as underwater distributuary channel with light grey and green grey sandstone have been further identified. As to the lake environment, shallow lake with green grey siltstone and mudstone, and swamp with black coal, carbonaceous mudstone and green grey mudstone have been further identified.

The grading analysis is commonly used in sedimentary rocks to help identify the sedimentary environments. Histogram, frequency graph, cumulative frequency curve and probability cumulative curve integrated with the related parameters as standard deviation, skewness and kurtosis to indicate the sedimentary characteristics (Shanbei Team of Chengdu College of Geology, 1978). The detailed development characteristics of each microfacies are shown in Table 1.

Identification Of Sequence Boundary And System Tracts

Our research team also have conducted large number of works about the sequence statigraphy and made detailed identification on it based on core observation, well-long analysis and seismic data and geochemistry (Hu, 2013; Wang, 2012; Yao, 2012).

5.1 Identification of sequence boundary

The sequence boundary during geological history is a physical interface and presents clear reflections on seismic profiles. It is the basic stratigraphic unit which is the product of base level changes that can be tracked and compared within the basin. In Meihe Formation, the seismic reflection commonly arrivals and terminates as onlap, toplap and truncation geometry, and truncates under the interface while onlaps in the interface of the sequence boundary. Two third-order sequence boundaries labeled as te2 and te3 and three thire-order sequences have been identified according to sudden change of well logs, lithological changes and reflection configuration of seismic profiles. Sequence I corresponds to the Lower Coal-beaing Member, Sequence II corresponds to the Mudstone Member (the bottom boundary is te2 and the top boundary is te3) and Sequence III corresponds to the Upper Coal-bearing Member. The sequence boundary of te2 is characterized by medium to high amplitude, intermediate frequency and continuous to discontinuous reflection. Onlap can be seen in both boundaries of te2 and te3 (Fig.4) (Hu, 2013; Wang, 2012; Yao, 2012).

Unconformity, sedimentary hiatus, exposure and stream channel incision etc. are familiar identification lithologic marks. Three completely different depositional systems are developed in the Meihe Formation, and from bottom to top the lithological association changed clearly. The Conglomerate to the Lower Coal-bearing Member mainly deposited fan delta sediments and thick coal seams of swamp, the Mudstone Member mainly deposited semi-deep to deep lake sediments of oil shale, siltstone and mudstone, while the Upper Coal-bearing Member mainly deposited fan delta front and shallow lake sediments. The thick coal seams of the Lower Coal-Bearing Member are directly covered by thick dark mudstones of the Mudstone Member, which indicates a hiatus exists between them(Fig. 2). Thick coal seams that mark the top of the Lower Coal-Bearing Member are comparable across the entire basin.

The sequence boundary of Meihe Basin is also can be recognized based on the sudden changes of well-log curves. At the surface of te2, the true resistivity (Rt) curve suddenly increases and the natural gamma-ray (Gr) suddenly decreases, which is the same to the surface of te1 (Fig.2). Besides, the sequence boundary is also an important transform surface of tectonic stress. The Mudstone Member was formed when the basin was mainly undergoing extensional stress, while during the deposition of the Upper Coal-Bearing Member, compressional stress is dominated the basin (Wang et al., 2008).

The above descriptions all indicate that sequence boundaries existed between the Lower Coal-bearing Member and the Mudstone Member (marked te1) as well as between the Mudstone Member and the Upper Coal-bearing Member (marked te2). Sequence I (the Lower Coal-bearing Member) and Sequence III (the Upper Coal-bearing Member) are the target strata of this article (Fig. 2).

5.2 Identification of system tract

The system tracts are the sedimentary systems formed during the same period, and this article adopts the division of each third-order sequence into LST, TST and HST (Olsen, 1990; Shanley, 1994; Vail, 1991). Rock association, well-log analysis and geochemistry are used to identify the system tracts of the Meihe Basin which has sufficient and rapid sediment supply and variable sedimentary environments. The first flooding surface and the maximum flooding surface are key factors dividing the system tracts and both of them present significant characteristics in the well-log curves and lithological changes. In Borehole MH2011-10, sudden changes in well-log values are observed at both the first flooding surface and the maximum flooding surface, and high gamma ray, low spontaneous potential with high resistivity values occurred in the maximum flooding surface (Fig. 2). Coarse sandstone of the fan delta plain sediments is covered by dark silty mudstone of fan delta front sediments at the first flooding surface, while at the maximum flooding surface, sandstone of fan delta front is directly covered by coal seams of swamp (Sequence I) or covered by coal or charcoal of fan delta plain (Sequence III).

Characteristic of parasequence sets is the key factor dividing the system tracts. LST mainly consists of progradational parasequence sets and upward in Meihe Formation, of each parasequence set, the thickness increases, the ratio of sandstone thickness versus mudstone thickness increases and the water shallows. TST is confined by the first flooding surface and the maximum flooding surface with the retrogradational parasequence sets, and for each parasequence set, the thickness decreases, the ratio of sandstone thickness versus mudstone thickness decreases with the sediments become finer and finer. In the TST of Sequence I, fan delta plain sediments changed to fan delta front sediments upward, while in Sequence III, the sediments changed from fan delta front to shallow lake then to fan delta front(Fig.2). HST mainly consists of aggradational and progradational parasequence sets. The sequence I of borehole MH2011-10 is not completely developed and the lower part of HST performs as aggradational parasequence set with little changes in the thickness and grain size, while the upper part of HST performs as progradational parasequence sets. Besides, the rare earth elements (REEs) also can be used to identify the system tracts (Tian e t al., 2006), the value of total REE content ($\sum$REE) is lowest in the LST, increases in the TST and reaches a maximum at the maximum flooding surface, while it decreases in the HST. All the information above is used to identify the LST, TST and HST of each sequence.

Results

6.1 Character of stratigraphic sequence

The descriptions above make it clear that the Lower Coal-bearing Member, the mudstone Member and the Upper Coal-bearing Member each correspond to a third-order sequence and are Sequence I, Sequence II and Sequence III, respectively. Sequence I and Sequence III both show development of the LST, TST and HST, and, as a parallel unconformity exists between Sequence I and Sequence II, only the TST and HST are developed in Sequence II (Fig. 2).

6.2 Distribution of sedimentary facies in the stratigraphic sequence

Lacking outcrop and seismic data, this article reconstructs the lithofacies paleogeography of each system tract in sequence using single-factor analysis and the multifactor comprehensive mapping method proposed by Feng (2004). Core observation, description and corresponding environmental facies analysis of 134 boreholes are used, and, combined with the analysis of the stratigraphic correlation of each exploration line, single-factor contour maps are derived. These maps include the sand content, total strata thickness, sandstone stratum and coal seams (both commercial and unworkable) as well as the number of layers within coal seams (commercial and unworkable).

6.3 Strata thickness, sandstone thickness and sand content

6.3.1 Sequence I (The Lower Coal-bearing Member)

LST: The contour map of strata thickness indicates that the thickest areas are mainly distributed in the north part of area A and in the northwest part of the studied area, which show fan-shaped or lobate-shaped deposition forms. The low thickness area that has few sediments is mainly located in the north part that is close to boundary fault F_1; The thickest sandstones are deposited mainly in the north part of area A, while the medium thickness areas are located in the southwest part, and the lower thickness areas are mainly located in the north and the northwest part; Areas of high sand content are mainly located in the north part of area A, the northwest part and southeast part, the medium sand content area is located in the south part close to boundary fault F_2 and the low sand content areas are all located close to the boundaries of the studied area. The above analysis shows that area A has the highest values of strata thickness, sandstone thickness and sand content, indicating that one major source direction from direction A’ existed during the LST of Sequence I (Fig. 5-1a).

TST: The thickest areas of stratum are mainly in the west part of area B and the southwest part, which show fan-shaped and lobate-shaped deposition forms; the medium thickness areas are located in the east part of area C and northeast part, while the thin stratum areas are distributed in both the north part and south part; The thickest sandstones are mainly deposited in the west part of area B, northwest part and east part of area C, while the thin sandstone area is mainly located in the north part close to boundary fault F_2; High sand content areas are mainly located in the west part of area B, north part and east part of area C, and the low sand content area is mainly located in the north part close to boundary fault F_2. The three maps above indicate that there might have been one major source from direction B’ and one secondary source from direction C’ (Fig. 5-1b).

HST: ①The thickest areas of the stratum and sandstone thickness are both mainly present in the northwest part of area D and the northeast part of area E, while the medium thickness areas are both mainly distributed in the north part and in area F, which have a fan-shaped distribution; The medium stratum thickness area is mainly in the north part and the medium sandstone thickness is widely distributed in the north part close to boundary fault F_1; ②Areas of high sand content are mainly distributed in area D, area E, area F and the northeast part close to fault F_1 and the southeast part close to fault F_2, while the low sand content area is mainly distributed in the north part close to the fault F_1. All of the above indicate that two major source areas existed during the HST of Sequence Ⅰ, from the direction D’ and the direction E’, and one secondary source area from the direction F’ (Fig. 5-1c).

6.3.2 Sequence Ⅲ (The Upper Coal-bearing Member)

LST: ①There are four high stratum thickness areas which are located in the west part, north part, northeast part of area G and central-south part, while the low value areas are widely distributed in the west part, north part and east part; ②The thickest area of sandstone is mainly in the southeast part of area G and south part, while the thin sandstones are mainly deposited both in the west part and southeast part; ③High sand content areas are mainly located in the south part close to fault F_2 and most of the west part, while the low sand content area is mainly distributed in the west part of the studied area. The above synthesis shows that during the deposition of the LST in Sequence Ⅲ, a single major source area from direction G’ can be postulated (Fig. 5-2d).

TST: ① Areas of high strata thickness and sandstone thickness generally have a fan-shaped distribution and are located in the west part of area H, northeast part of area I and central-north part, while the low thickness areas are both distributed in the north part and south part, but are more widely distributed in the south part; ②Areas of high sand content are mainly distributed in most of the east part, the west part of area H, and a small area of the south part, while the low sand content areas are only located in a small area of the north part. The above analysis shows that there may have been two major source areas; from direction H’ and direction I’ (Fig. 5-2e).

HST: ① Two areas of high strata thickness exist in the north part close to the

boundary fault F_2 and exhibit a fan-shaped distribution; ②Similar to the stratum thickness, the sandstone thickness also has two high value areas located in the north part, while the low thickness areas are widely distributed in the north part, west part and east part; ③ Two areas of high sand content exist with limited distribution in the north part and more widely so in the west part. These results indicate that one major source existed, from direction J’ (Fig. 5-2f).

6.4 Distribution of coal seams

The Meihe Basin is a fault basin with widely distributed coal seams. Commonly, coal seams thicker than 0.5 m are considered as commercial in the Meihe Basin, while coal seams thinner than 0.5 m are considered unworkable seams of no economic value. This article studies the commercial and unworkable coal seams separately and discusses their accumulated thickness, layering, vertical distribution (Fig. 6) and planar distribution (Fig. 7) in various system tracts of different sequences, and further studies the distribution relationship between coal seams and sedimentary environments.

6.4.1 Sequence I (The Lower Coal-Bearing Member)

LST: Commercial coal seams are not well developed in the LST of Sequence I. Vertically, a few discontinuous thin coal seams of fan delta plain facies are developed, and the range of coal accumulation is wider in the southeast part than northwest part (Fig. 6). Statistics from 134 boreholes show that unworkable seams have a wide distribution with an aggregate thickness range of 0.08 m-3.14 m and maximum layers of 14 of all coal in individual boreholes, with the range of thickness of single seams being 0.06 m-0.49 m (average 0.19 m). The thickness and number of layers both decrease from the northeast part close to boundary fault F_2 to the northwest part close to boundary fault F_1. Based on the contour maps of stratum thickness, sandstone thickness and sand content, a lithofacies palaeogeography map has been produced. As can be observed on the map, the fan delta facies presents a growth trend from the south part to the north part. Fan delta plain, fan delta front and shallow lake facies are the main sedimentary subfacies and shallow lake sediments are mainly distributed in the area close to boundary fault F_1 (Fig. 7-1a). Coal seams are mainly accumulated in the fan delta plain facies and are distributed in the areas with medium stratum thickness and low sand content (Fig. 5-1a). Coal accumulated in the fan delta plain is easily influenced by sediment supply and channel realignment, thus forming unstable thin coal seams with large numbers of layers which are unworkable.

TST The coal seams of the TST in Sequence I have a wider distribution compared to the LST and present as discontinuous and thin at the bottom, thickening upward. On the top layers of the LST, the coal seams are thicker and more continuous (Fig. 6). Statistics show that the commercial coal seams are mainly distributed in the northwest, southeast and northeast part of the studied area (Fig. 7-1b). Total thickness within single boreholes has a range of 0.04 m-7.55 m, with a maximum of 34 layers, while the thickness of single seams has a range of 0.04 m-0.49 m (average 0.22 m). Coal seams are thick in the south and thin in the north and are mainly distributed in the southeast part. Sediments of fan delta plain and fan delta front facies are mainly deposited in the northeast and west part of the studied area, and, compared to the LST, the fan delta facies has a narrower distribution. Coal seams mainly accumulated in the swamp facies, which has large stratum thickness and low sand content (Fig. 5-1b). The swamp environment is distal to the source areas and is influenced little by waves and channel migration, thus forming large thicknesses and stable distributions. It is the first commercial coal accumulation stage of the Meihe Basin.

HST Coal seams tend to migrate to the northwest part in the HST of Sequence I. Commercial coal seams mainly accumulated in the northwest and northeast part, as well as in a limited area of the southwest part (Fig. 7-2c). Statistics show that the total thickness of the commercial coal seams in single boreholes can be as high as 45.19 m, with a maximum of 14 layers, and the thickness range of single coal seam is 0.5 m-25.08 m (average 2.46 m). The unworkable coal seams mainly accumulated in the southwest part with a total thickness range of 0.15 m-4.88 m, a maximum of 28 layers in a single borehole, with the thickness range of single seams being 0.03 m-0.49 m (average 0.21 m). The fan delta sediments are mainly distributed close to boundary fault F_2, with small distributions deposited in the northeast and west parts. Swamp is the main coal-accumulating environment and coal seams are mainly distributed in the north part close to boundary fault F_1 (Fig. 7-2c). The fan delta sand body has little influence on coal accumulation, and large thickness, predictably distributed coal seams with greater economic value are deposited in the HST of Sequence I. Vertically, coal seams are thicker than in the TST, and thicken upward. During the last stage of the HST, coal seams are thickest and most continuously distributed, and the most commercially important 12th coal seam was formed during this stage (Fig. 6).

In general, during the deposition of Sequence I, fan delta plain and swamp are the main coal-accumulating environments and fan delta plain sediments are mainly distributed in the LST while swamp sediments are mainly distributed in the TST and HST. During the cycle of LST to TST to HST, the distribution of shallow lake facies tends to be narrower, the distribution and thickness of coal seams tend to be larger and coal-accumulating environments are transformed from fan delta plain to swamp facies. The TST is the first stage of formation of commercial coal seams and the HST is the second and most important stage for commercial coal seam accumulation.

6.4.2 Sequence III (The Upper Coal-Bearing Member)

LST: Commercial coal seams in the LST of Sequence III are distributed in limited areas of the north part, and the total thickness range in single boreholes is 1.67 m-1.93 m with one or two layers developed, with single coal seams having a thickness range of 0.73 m-1.93 m (average 1.2 m). Unworkable coal seams are mainly distributed in the northwest part of the studied area, with a total thickness range of 0.17 m-2.27 m, a maximum of 13 layers in a single borehole, with the thickness range of single coal seams being 0.04 m-0.48 m (average 0.25 m). Fan delta is the main depositional environment and the sediments cover more than half of the studied area, with shallow lake sediments mainly distributed in the southwest part. Interchannel swamp of fan delta plain is the main coal accumulating environment (Table 1), and coal seams are unworkable with thinner and discontinuous distribution and large numbers of layers.

TST: Compared to the LST, coal seams are deposited in the fan delta plain and are widely distributed. However, as a whole, the seams are thin and discontinuous. Vertically, relatively continuous single coal seams are developed in the bottom and middle layers as well as the top layers of the TST (Fig. 6). The commercial coal seams are mainly distributed in the central part of the studied area (Fig. 7-3e) with a total thickness range of 0.5 m-15.06 m and a maximum of 8 layers in a single borehole, with single seam having a thickness range of 0.5 m-7.58 m (average 1.24 m). The unworkable coal seams have a wider distribution with the no-coal area distributed only in small areas of the north part, east part and south part (Fig. 7-3e). The total thickness range of unworkable coal seams in single borehole is 0.13 m-2.98 m with a maximum of 10 layers, while single coal seams have a thickness range of 0.04 m-0.49 m (average 0.27 m). Shallow lake sediments are widely distributed in the central part, and a small portion of swamp is distributed close to boundary fault F_1. Fan delta sediments are widely distributed in the east and west parts and fan delta plain coal-accumulating areas are mainly located in the east and northeast parts of the study area (Fig. 7-3e).

HST: The coal seams are relatively thin and discontinuous, and in the bottom of the HST some relatively continuous thin coal seams are accumulated (Fig. 6). The coal distribution is narrower compared to the TST and is mainly limited to the central part of the studied area (Fig. 7-3f). The commercial coal seams have a total thickness range of 0.61 m-14.83 m with a maximum of 12 layers, while single coal seams have a thickness range of 0.52 m-5.71 m (average 1.31 m). The unworkable coals seams have an aggregate thickness range of 0.23 m-2.42 m and a maximum layer of 8 in individual boreholes, and the thickness range of single coal seam is 0.07 m-0.48 m (average 0.27 m). Fan delta sediments are widely distributed in southwest part of the studied area and coal is mainly accumulated in the fan delta plain interchannel swamp facies. The coal-accumulating center is located close to boundary fault F_1 (Fig. 7-3f).

In Sequence Ⅲ, coal is distributed in a narrower range with lower thickness compared to Sequence Ⅰ, and fan delta sediments are distributed more widely while shallow lake sediments are distributed more narrowly. Coal is mainly accumulated in the fan delta plain with little economic value, with the TST and HST of Sequence Ⅲ being the third and fourth coal-accumulating stages of the Meihe Basin, respectively.

Discussion

Previous studies have shown that during the deposition of both sequence Ⅰ and sequence Ⅲ are in relatively stable structural settings (Wang et al., 2008). Based on the maps of sedimentary distribution, coal seam correlation, stratum thickness and sand content etc., coal of the Meihe Basin is mainly accumulated in flat depressions with little influence from sediment supply and channel migration. Plants were growing rapidly in the warm and humid paleoclimate and peat accumulated rapidly in the freshwater environment, thus offering sufficient organic matter for coal accumulation (Bai et al., 2014b; Hu, 2013). Each of the above conditions have prompted the formation of coal in the Meihe Basin.

The controlling factors of sequences are different in marine and non-marine basins (Liu et al., 2002), but in both environments, coal accumulation is related to the variations of both base level and accommodation space. The theory of base-level cycles is applicable to both of the two types of basins (Holz and Kalkreuth, 2002; Shao et al., 2003a). Additionally, a reducing environment is essential and is most important

for peat accumulation among all the factors, and a relatively high and consistently rising lake level can effectively reduce the oxygen supply (China National Administration of Coal Geology et al., 2001; Lv and Chen, 2014). In the warm and humid paleoenvironment, stable structural settings and reducing environment, coal seams in both sequences mainly accumulated in the TST and HST.

During the deposition of the LST, lake levels tend to be lower and the accommodation space is reduced. The growth rate of accommodation is lower than that of peat accumulation, which reduces the potential for coal accumulation. Additionally, fan delta sediments are developed and channels are migrating frequently, both of which developments are destructive to coal seams. Under the circumstances, peat accumulation only occurs in a few depressions, and the coal seams formed are thin and discontinuous and have no economic value.

During the early stages of the TST, lake levels are rising and the rate of growth of accommodation space is higher than peat accumulation rate, and thus the basin expands. In the late stages of the TST, rises in lake levels are slowed and even stopped, while the sediment supply still continues, and the lake easily silts up. When the deposition rate is balanced with the peat accumulation rate for a relatively long time and fewer outside factors affect the area, thick and continuous widely distributed coal seams are accumulated in Sequence I (Fig. 8a). However, in Sequence III the coal seams of the TST are thin and discontinuous and are limited in their distribution as lake sediments are limited and the swamp facies is not developed; sediment supply is sufficient, and fan delta sediments therefore become widely distributed.

During the deposition of the HST, lake levels tend to be stable at first and decrease later. Fan delta construction and destruction alternate and the widely distributed coal-bearing layers are mainly accumulated in the abandoned fan delta lobes. During the late stage of the HST, sediment progradation from the lakeshore occurs and the lake starts silting up. When long-term balance exists between the growth rate of accommodation space and the rate of peat accumulation, thick commercial coal seams in swamp environments are formed in Sequence I. Thick commercial coal seams are also accumulated in the linked environments of silted-up shallow lakes and abandoned fan delta lobes when the conditions are suitable for peat accumulation in Sequence I (Fig. 8a). In Sequence III, limited by the distribution range of lake sediments and by the influence of, for example, sediment supply and channel migration, only a small number of discontinuous and thin coal seams were accumulated in the Meihe Basin (Fig. 8b). However, on the whole, the paleogeographic characteristics of the HST are similar to the TST.

In a third-order sequence, coal accumulation varies among the various sedimentary environments in different system tracts or in different stages of the same system tract. Therefore, the temporal and spatial distributions of coal-rich zones migrate. Overall, both the TST and HST have the potential to balance the rate of accommodation growth and the rate of peat accumulation, and therefore accumulate widely distributed commercial coal seams. In the other observed sedimentary environments and structural settings, different thicknesses and distributions of coal seams are formed in Sequence I and Sequence III.

Conclusions

Fan deltas and lakes are the main sedimentary environments of both the Lower Coal-bearing Member and the Upper Coal-bearing Member. Fan delta plain, fan delta front, shallow lake and swamp are the main sedimentary subfacies, and among them interchannel swamp of fan delta plain and swamp are the main coal accumulating environments.

There are three third-order sequences; the Lower Coal-bearing Member is Sequence I, and the Mudstone Member is Sequence III. The LST, TST and HST are developed in both of these sequences.

Fan delta plain is the main coal accumulating environment of the LST in Sequence I, where the coal seams are thinner and discontinuous and have no economic value; coal seams of the TST and HST of Sequence I are mainly accumulated in swamp environments which are thin, continuous and widely distributed and are commercial to mine; coal seams in the LST of Sequence III are limited in distribution and are accumulated in the fan delta plain environment, and the coal has no economic value; coal in the TST and HST of Sequence III also accumulated in the fan delta plain environment with a wider range of distribution comparable to the LST, and the coal seams are relatively thin and have little economic value.

The TST and HST are the primary coal accumulating stages of the Meihe Basin, during which stages the growth rate of accommodation space was balanced with the rate of peat accumulation. This phenomenon contributed to the formation of coal. The swamp facies has a wide distribution and was influenced less by the sediment supply and channel migration and thus formed stable coal accumulating environments.

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Table

Table 1 Characteristics of the main sediments of coal-bearing layers (Bai et al., 2014a, some contents revised and added)

<table>
<tr><th colspan="3">Sedimentary Facies</th><th rowspan="2">Lithology</th><th colspan="5">Grading analysis</th><th rowspan="2">Well-long analysis</th></tr>
<tr><th>Facies</th><th>Subfacies</th><th>Microfacies</th><th>Histogram</th><th>Standard deviation</th><th>Skewness</th><th>Kurtosis</th><th>Probability cumulative curve</th></tr>
<tr><td rowspan="6">Fan delta</td><td rowspan="3">Fan delta plain</td><td>Distributary channel</td><td>The distributary channel mainly consists of red, light grey and mingled conglomerate, sandy conglomerate and pebbly sandstone with poor structure maturity and component maturity. The erosional surface, trough cross bedding and normal graded bedding can be seen(Fig.3a,b).</td><td>Double peak</td><td>0.72</td><td>-0.13</td><td>0.91-1.03</td><td>Mainly consists of two-stage curves, one-stage and three-stage curves also exist.</td><td>Medium to high-amplitude bell shape and serrated cylinder shape.</td></tr>
<tr><td>Distributary interchannel</td><td colspan="6">The interchannel mainly consists of red and dark grey siltstone and mudstone with the interbedded fine sandstone.</td><td>Medium-amplitude serrated shape</td></tr>
<tr><td>Fan delta plain marsh</td><td colspan="6">The sediments are mainly dark coal and carbonaceous mudstone with interbedded sandstone. It is the main coal accumulation environment of fan delta.</td><td>Low to medium-amplitude box shape and bell shape</td></tr>
<tr><td rowspan="3">Fan delta front</td><td>Underwater distributary channel</td><td>The underwater distributary channel mainly consists of light grey and grey coarse to fine sandstones. The climbing ripple bedding , deformed bedding and bioturbation can be seen in the core(Fig.3c,d,e).</td><td>Single peak</td><td>Average 0.77</td><td>Average 0</td><td>0.8-1.2</td><td>Mainly are two-stage and three-stage curves.</td><td>Medium to high-amplitude box shape and bell shape.</td></tr>
<tr><td>Underwater distributary interchannel</td><td>The interchannel mainly consists of dark grey siltstone and mudstone with large amount of charcoals in it.</td><td>Single peak</td><td>Average 0.49</td><td>Average -0.13</td><td>Average 1.03</td><td>Mainly are one-stage curves.</td><td>Serrated line shape.</td></tr>
<tr><td>Mouth bar</td><td>Coardening upward as a whole, the lower</td><td>Single peak</td><td>Average 0.45</td><td>Average -0.05</td><td>Average 1.12</td><td>Mainly are two-stage and double-</td><td>Low to medium-amplitude</td></tr>
</table>

			part consists of dark gray mudstone and siltstone, the upper part consists of medium to fine sandstones, bioturbation and deformed bedding can be seen in the core (Fig.3f).					leap three-stage curves.	serrated funnel shape.
		Sheet sand	Gray fine sandstone and siltstone interbedded with mudstone are the main sediments, the climbing ripple bedding, current bedding and bimodal cross-bedding are common (Fig.3g,h).	Single peak	Average 0.42	Average -0.09	Average 1.07	Mainly are two-stage curves with large slope in the curves of jump components.	Low to medium-amplitude serrated finger shape.
Lake	Shallow lake		The sediments are mainly light grey fine sandstone and siltstone, green grey siltstone and mudstone with large amount of charcoals in it, the current bedding, rhythmic bedding, burrows and fossils are common(Fig.3i,j,k).						Medium to high-amplitude serrated box shape and finger shape.
	Swamp		The sediments are mainly consist of thick coal seam and carbonaceous mudstone, the underlayer commonly is shallow lake sediments. It is the important environment for the coal accumulation of Meihe Basin(Fig.3l).						Serrated line shape and finger shape.

Figures

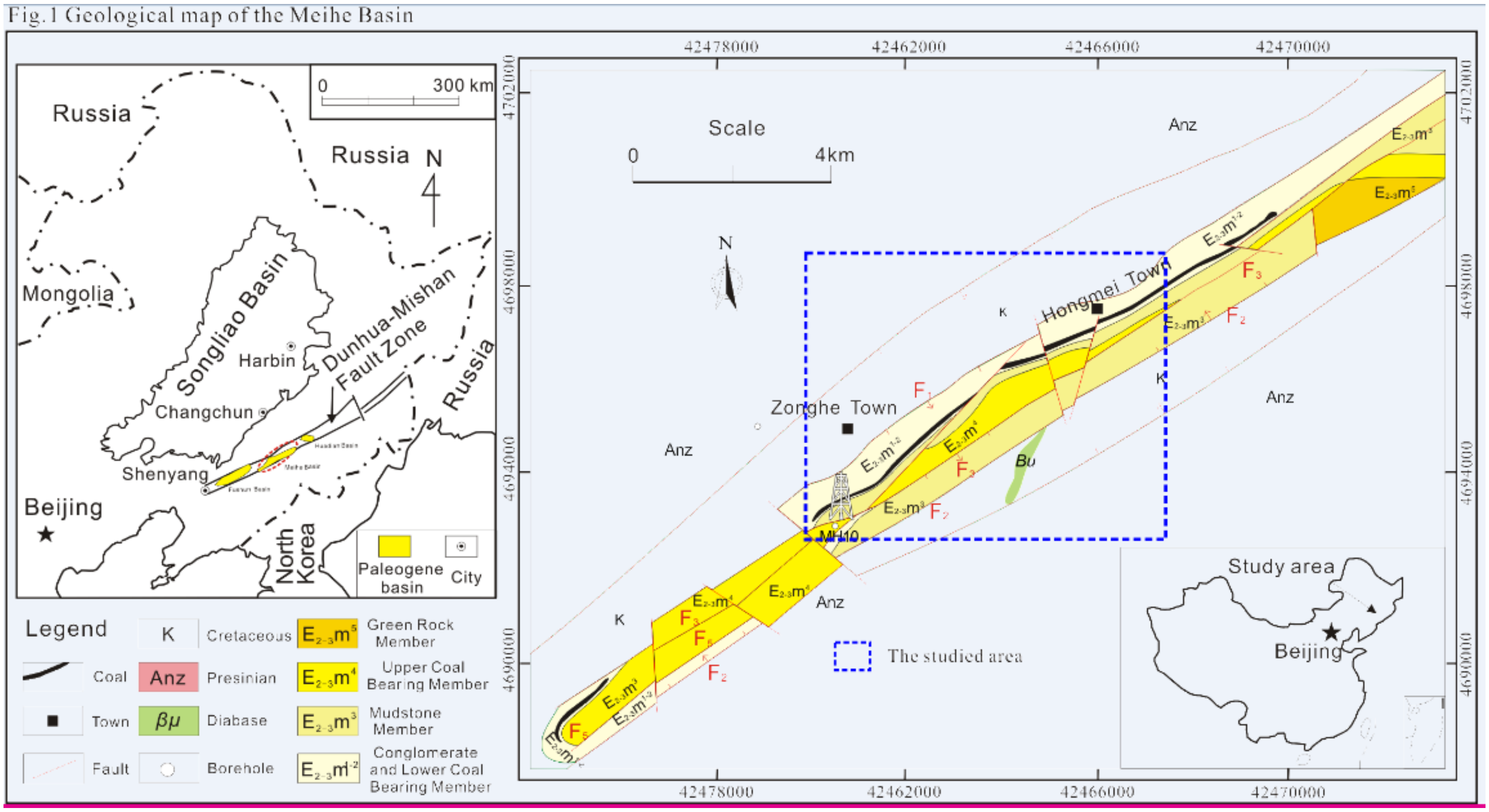


Figure 1

Geological map of the Meihe Basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

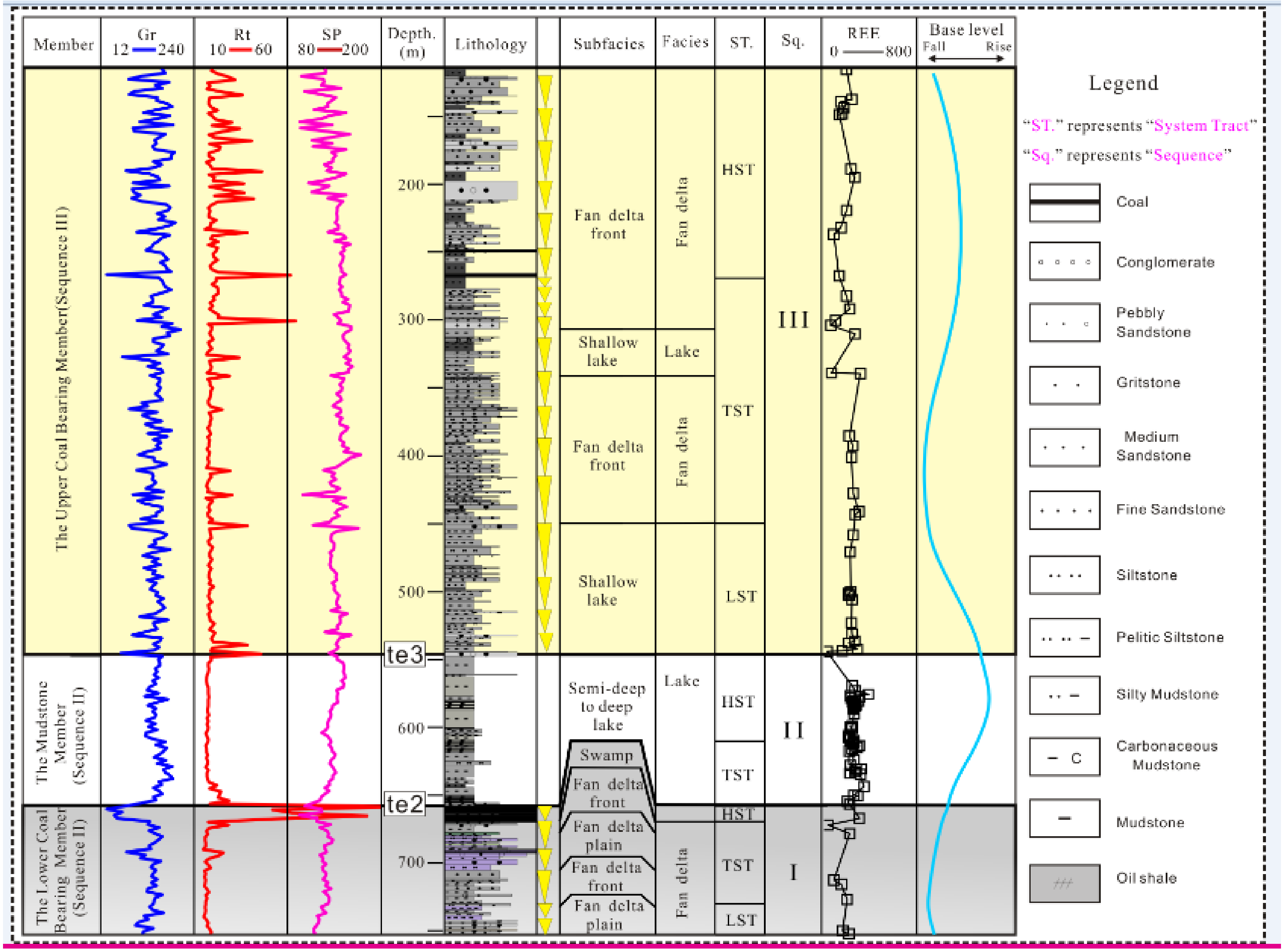


Figure 2

Characteristics of Sequence I and Sequence III of Borehole MH2011-10.

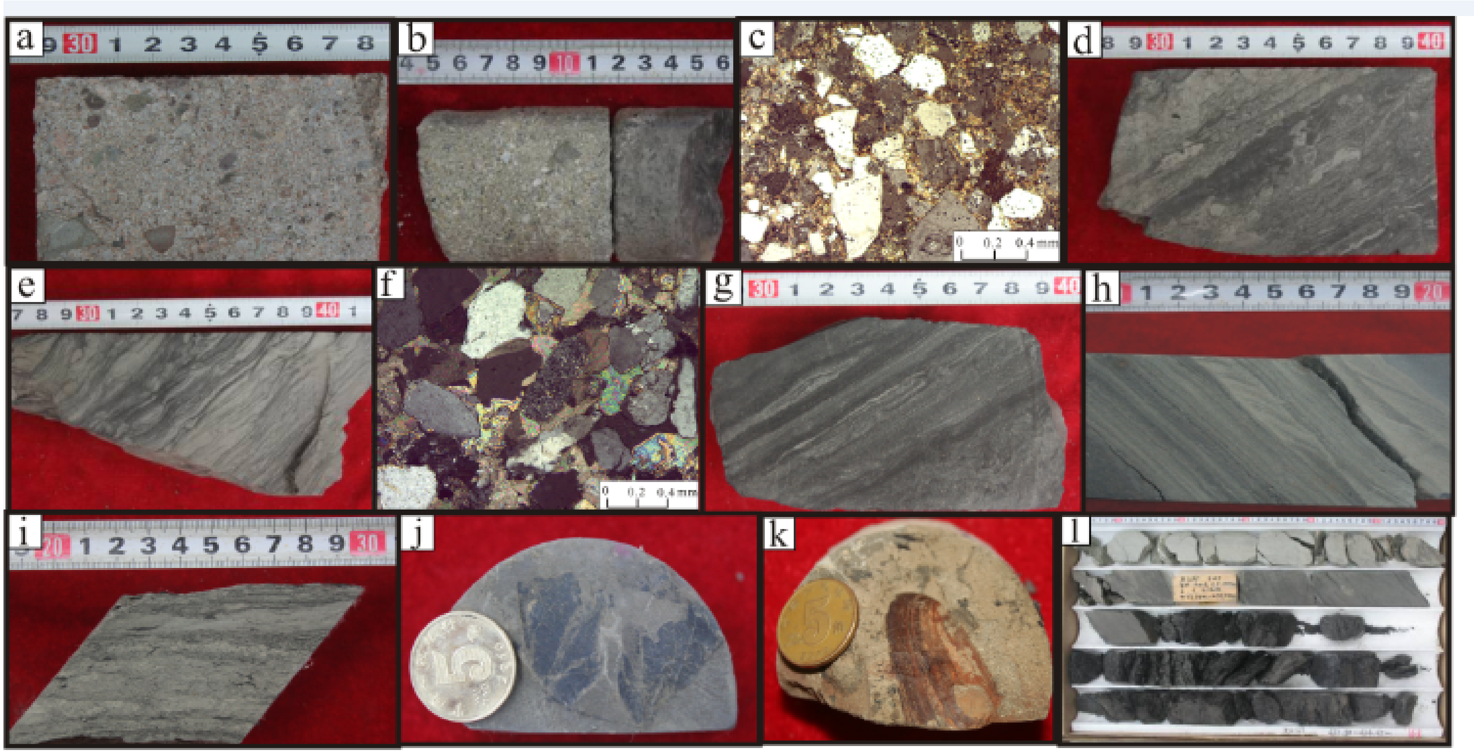
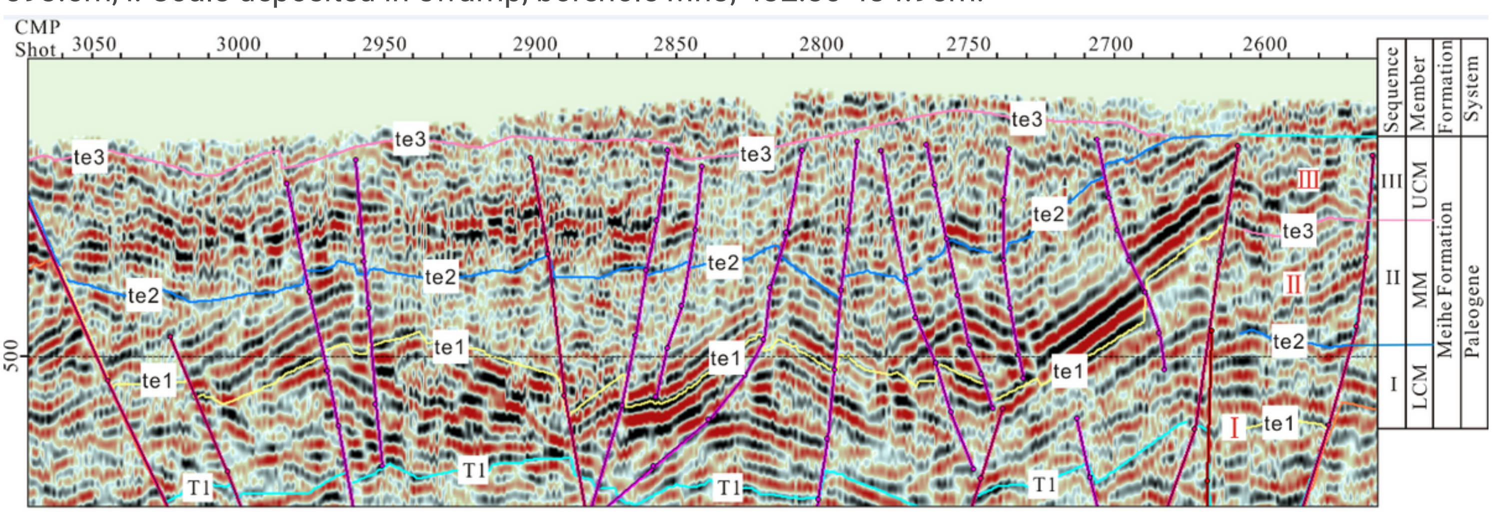


Figure 3

Core and microscopic pictures of different sedimentary environments. a. Conglomerate with poor component and textural maturity in fan delta plain, borehole MH2011-10, 694.40m; b: Erosional surface of fan delta front, borehole Mh3, 315.48m; c.Poor sorted medium sand stone in underwater distributary channel, borehole MH2011-10, 680.2m; d. Bioturbation of fan delta front, borehole Mh3, 525.65m; e. Current bedding of fan delta front sheet sand, borehole MH2011-10, 493.80m; f. Well sorted fine sandstone in mouth bar, borehole Mh3, 642.5m; g. Wavy bedding and bioturbation strutures developed in sheet sand, borehole Mh3, 624.1m; h. Climbing ripple bedding and current bedding in sheet sand, borehole Mh3, 212.90m; i. Large amounts of charcoals developed in shallow lake, borehole Mh3, 560.5m; j. Plant leaves in shallow lake, borehole Mh3,119.5m; k. Shell fossils in shallow lake, borehole Mh3, 593.5m; i. Coals deposited in swamp, borehole Mh3, 432.80-434.95m.



UCM indicates the Upper Coal-bearing Member; MM indicates the Mudstone Member; LCM indicates the Lower Coal-bearing Member.

Figure 4

Seismic cross-section of line 768 in Meihe Basin (Wang, 2012).

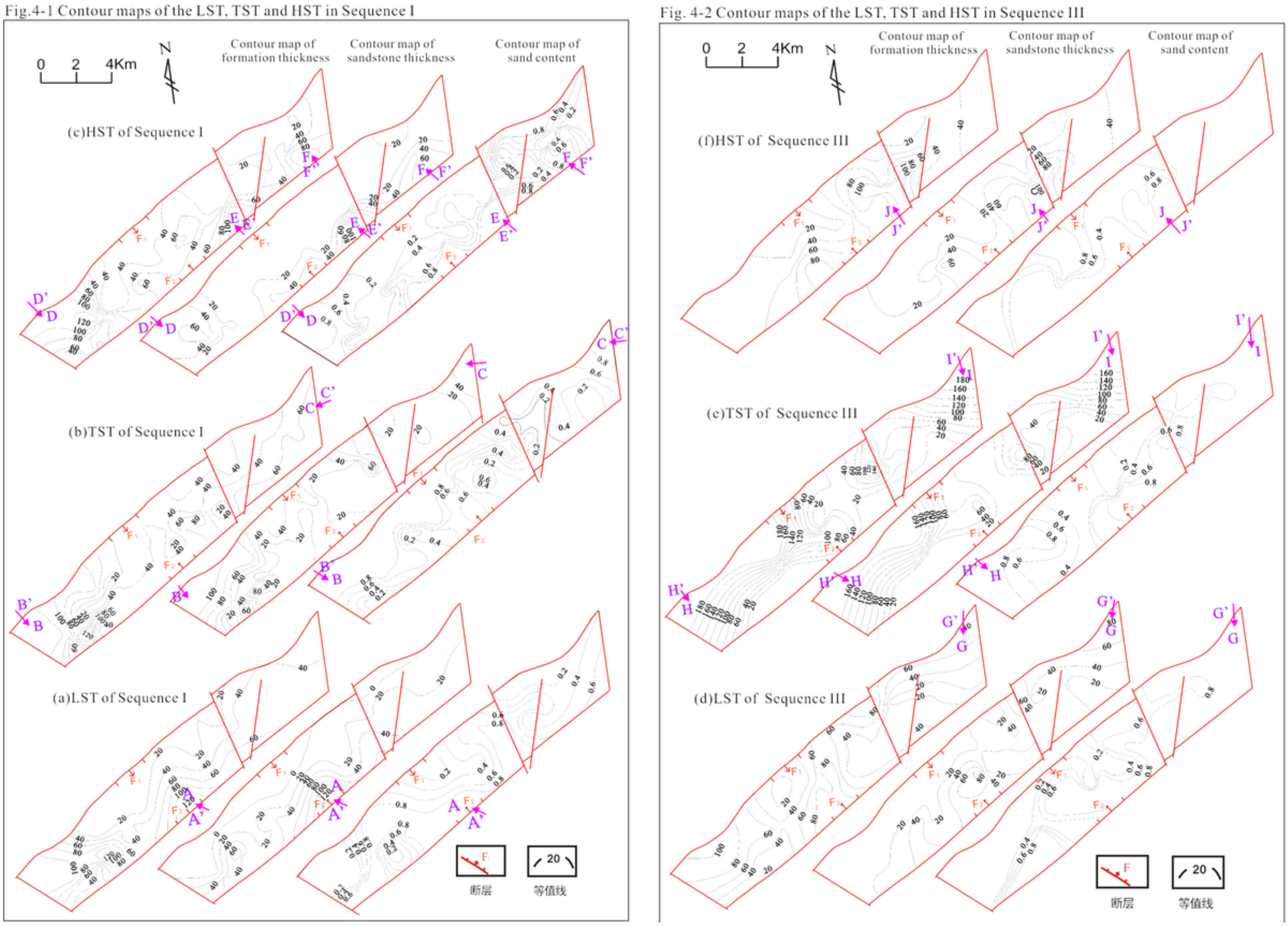


Figure 5

Fig. 5-1 Contour maps of total stratum thickness, sandstone stratum thickness and the ratio of sand content of the LST, TST and HST in Sequence I Fig. 5-2 Contour maps of total stratum thickness, sandstone stratum thickness and the ratio of sand content of the LST, TST and HST in Sequence III

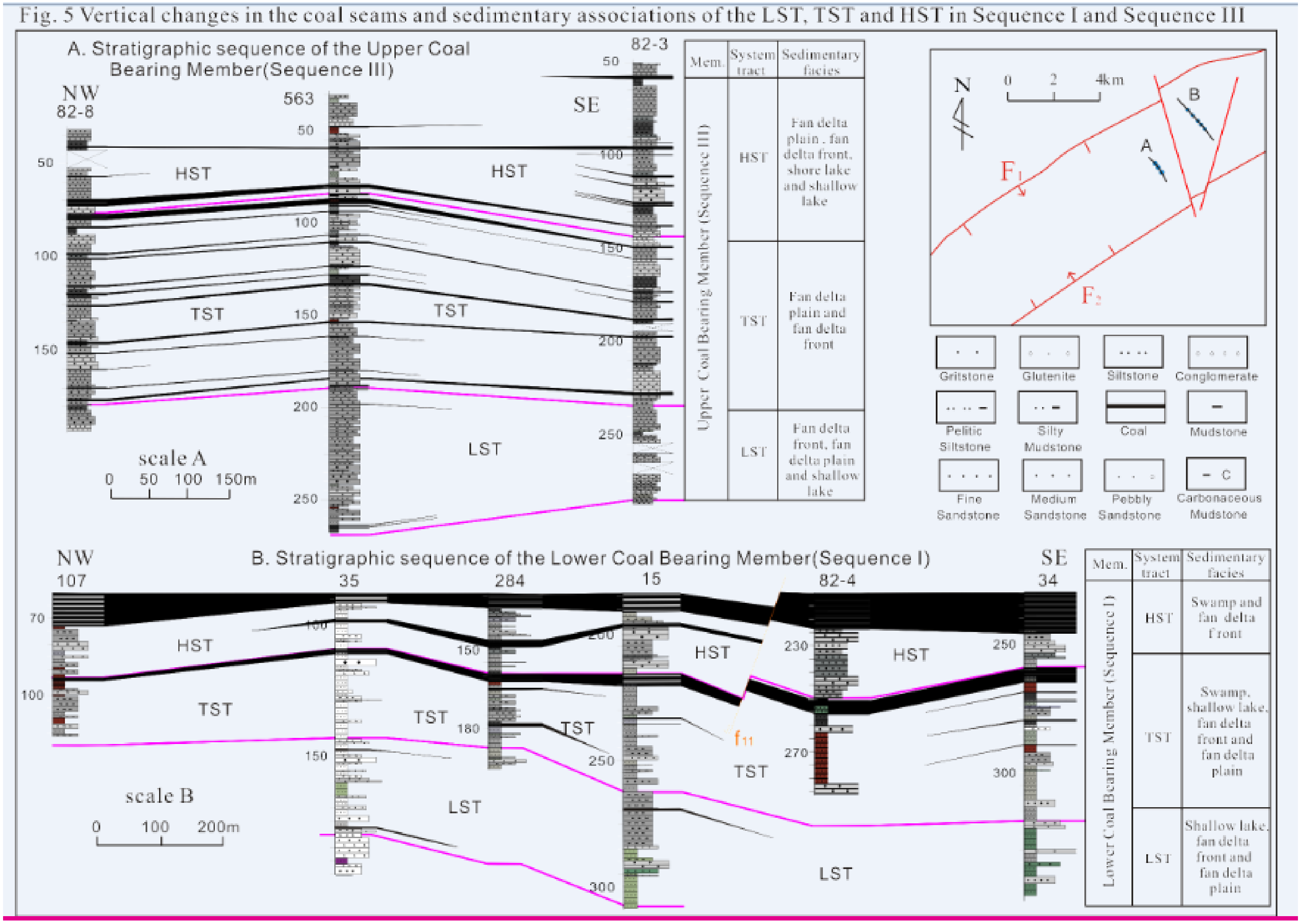


Figure 6

Vertical changes in the coal seams and sedimentary associations of the LST, TST and HST in Sequence I and Sequence III

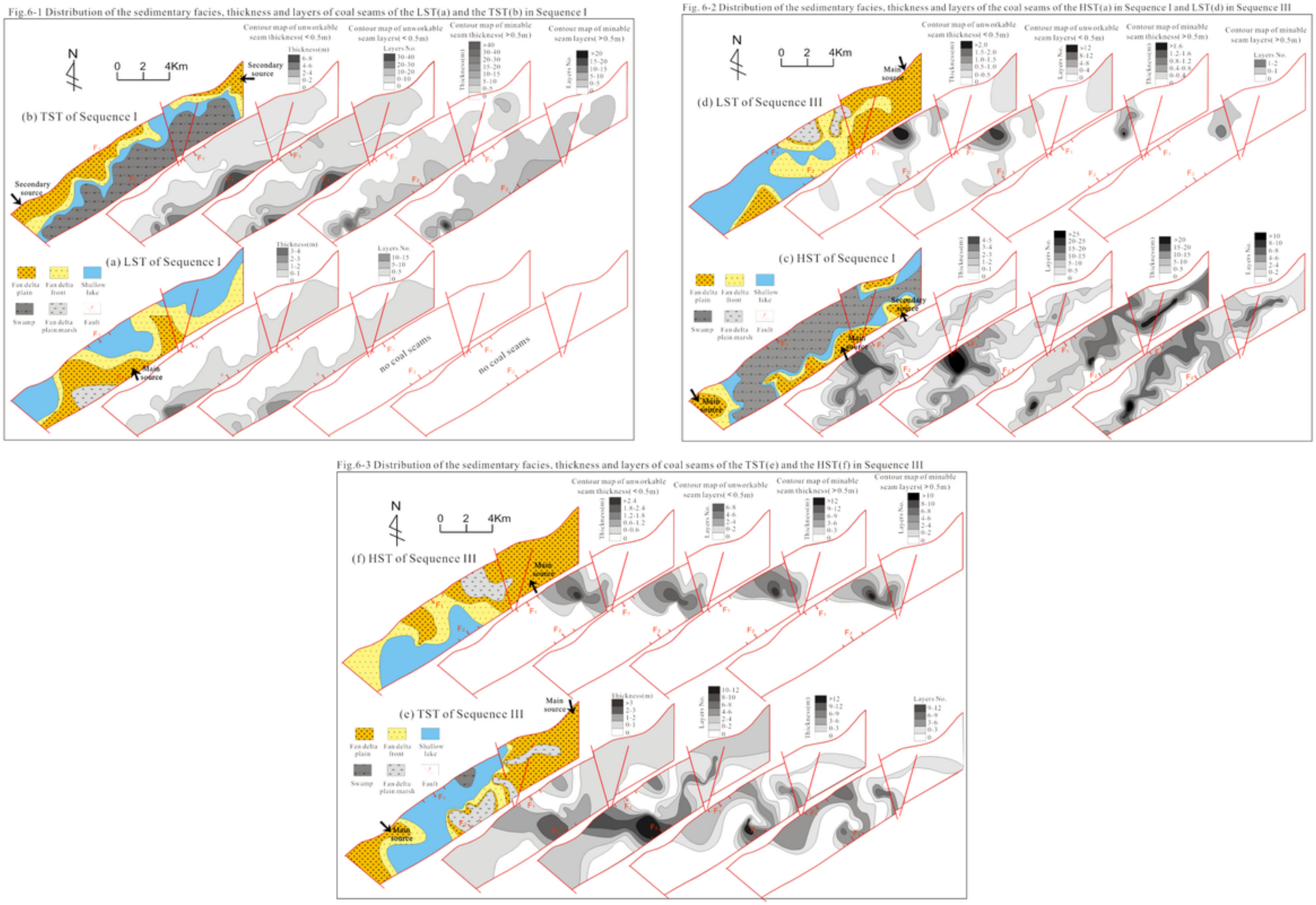


Figure 7

Fig 7-1 Distribution of the sedimentary facies, thickness and layers of coal seams of the LST (a) and the TST (b) in Sequence I Fig 7-2 Distribution of the sedimentary facies, thickness and layers of coal seams of the HST (c) in Sequence I and the LST (d) in Sequence III Fig 7-3 Distribution of the sedimentary facies, thickness and layers of coal seams of the TST (e) and the HST (f) in Sequence III

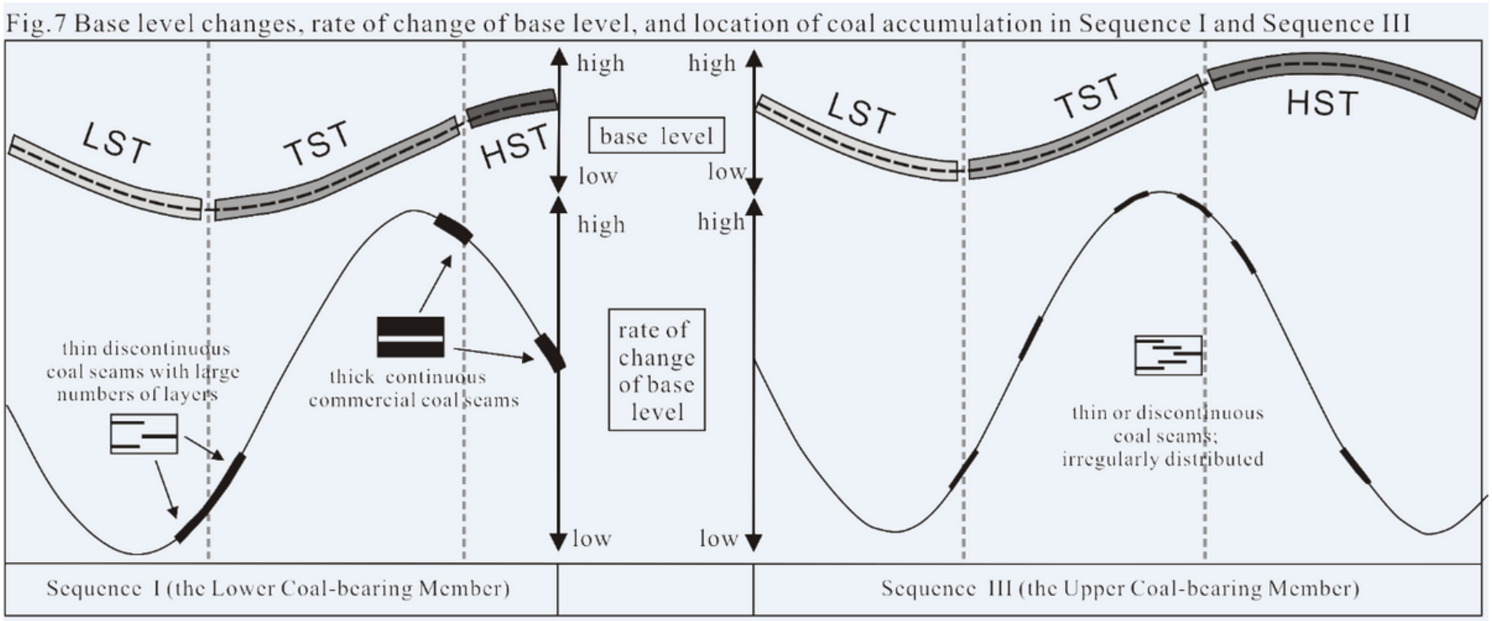


Figure 8

Base level changes, rate of change of base level, and location of coal accumulations in Sequence I and Sequence III (Modified according to Bohacs and Suter (1977))

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